Rainfall measurement using radio links from cellular communication networks

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[1] We investigate the potential of radio links such as employed by commercial cellular communication companies to monitor path-averaged rainfall. We present an analysis of data collected using two 38-GHz links during eight rainfall events over a 2-month period (October–November 2003) during mostly stratiform rainfall in the Netherlands. Comparisons between the time series of rainfall intensities estimated using the radio links and those measured by a nearby rain gauge and a composite of two C band weather radars show that the dynamics of the rain events is generally well captured by the radio links. This shows that such links are potentially a valuable addition to existing methods of rainfall estimation, provided the uncertainties related to the reference signal level, signal level resolution, wet antenna attenuation, and temporal sampling can be resolved.

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1. Introduction

[2] Digital fixed radio systems, the type of wireless communication networks employed by commercial cellular communication companies, have recently been proposed as a cost-effective means for regional rainfall monitoring, complementing existing monitoring systems such as rain gauge networks and weather radars [*Messer et al.*, 2006]. The number of links in commercial networks in the Netherlands ($\sim$35,000 km^2) is approximately 12,000, with an average length of the links comprising these networks between 3 and 4 km, resulting in a density of approximately 1 km km^{-2}. This very high density offers great potential for the use of these systems in combination with the network of operational weather radars.

[3] The fact that the propagation of radio waves in the atmosphere is hampered by rainfall along the signal propagation path has been known for a long time. Telecommunication engineers have studied the physical relation between radio wave attenuation and rainfall intensity since the 1960s [e.g., *Hogg*, 1968; *Semplak and Turrin*, 1969; *Crane*, 1971; *Olsen et al.*, 1978]. Their objective was to establish statistical relations between the probability distribution of rainfall and that of attenuation for different climatologies and radio wave frequencies, in order to be able to predict the desired attenuation statistics from the relatively abundant rainfall statistics.

[4] However, what is "noise" in telecommunication engineering can be considered "signal" in the geophysical sciences. The idea of using the attenuation of radio waves to estimate rainfall intensities is certainly not new [e.g., *Atlas and Ulbrich*, 1977; *Jameson*, 1991; *Giuli et al.*, 1991; *Minda and Nakamura*, 2005]. The employed rainfall retrieval method is based on measurements of the received signal level, estimation of the rain-induced attenuation, and the application of a power law relation between attenuation and rain rate to estimate path-averaged rain rate [e.g., *Olsen et al.*, 1978]. Recently, the development of dual-frequency radio links has given a boost to research in this area [e.g., *Rincon and Lang*, 2002; *Rahimi et al.*, 2003]. Rainfall estimation based on microwave attenuation is also used in space-borne radar retrieval algorithms [e.g., *Meneghini et al.*, 1992]. Radio links have also been suggested as tools to estimate both path-averaged precipitation and evaporation [*Leijnse et al.*, 2007a, 2007b]. The main objective of this paper is to demonstrate the potential and discuss the limitations of commercial cellular communication links for rainfall monitoring (contrary to the work of *Leijnse et al.* [2007b], where a research microwave link was used).

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2. Methods and Materials

2.1. Physical Basis

[5] Assuming the effects of multiple scattering to be negligible, the relative decrease in power between the source of a radio signal and a point in space (at a distance L from this source) due to attenuation by rainfall is given by [e.g., *Battan*, 1973]

$$\frac{P(L)}{P_0(L)} = \exp\left(-\frac{\ln(10)}{10}\int_0^L k(s)\mathrm{d}s\right), \tag{1}$$

where $P_0(L)$ is the received power without attenuation by rainfall, $P(L)$ is the received power and $k(s)$ (dB km^{-1}) is the specific attenuation due to rainfall as a function of the distance along the link s (km). $P_0(L)$ depends on the antenna size and radiation pattern, the transmit power and it decreases as L^{-2}. Measuring the signal power using a receiver at a distance L, the path-integrated attenuation (in dB) can be derived. The objective is now to estimate the average rainfall intensity over the total path of the link from

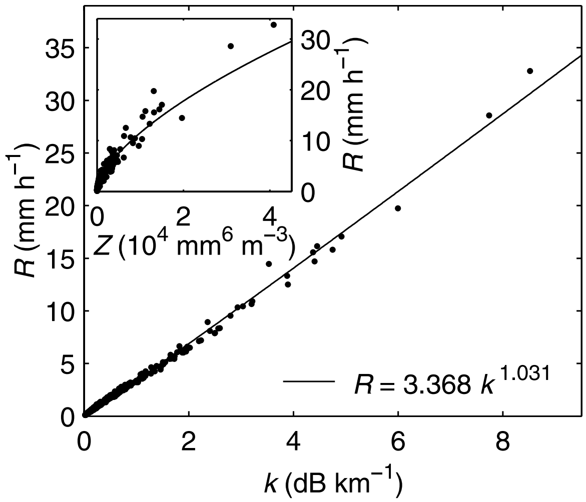

Figure 1. Nonlinear fit of a power law *k-R* relation using the drop size data of *Wessels* [1972]. The inset shows the relation between *Z* at C band (5.6 GHz, the KNMI radar frequency) and *R* using the same drop size data along with the power law *Z-R* relation used by KNMI.

the measured attenuation, using a relation between *k* and the rainfall intensity *R* (mm h^{-1}).

[6] The specific attenuation *k* is a function of the extinction cross section of the drops (and hence of the drop diameter) for the given frequency, whereas *R* is a function of the drop volumes and velocities. Through these size dependencies, both *k* and *R* depend on the drop size distribution in rain. At radio frequencies, scattering of electromagnetic waves off spherical raindrops can be computed using Mie theory [*van de Hulst*, 1957]. If drop shapes deviate from spheres, the polarization of the electromagnetic signal becomes relevant. However, as this is a minor issue for small drops, which are most abundant [*Pruppacher and Klett*, 1997], we assume the drops to be spherical. For the frequency employed in this paper (38.530 GHz, see section 2.2), we have used 446 drop size distributions measured by *Wessels* [1972] during more than one year in the Netherlands to fit a climatological power law relation between *k* and *R* for Dutch conditions.

[7] Figure 1 shows these data and a power law *k-R* relation obtained through nonlinear fitting. The limited scatter of the data points around this power law shows that the coefficient of the power law $R = ak^b$ is relatively insensitive to the type of rainfall and the associated drop size distributions for Dutch circumstances. This is confirmed by the low value of the coefficient of variation (the ratio of the standard deviation and the mean) of *a* (assuming $b = 1.031$), $CV_a = 0.15$, which is reduced to $CV_a = 0.06$ if only those points with $R \geq 2$ mm h^{-1} are considered. Similar conclusions about the insensitivity to the drop size distribution have been drawn by, for example, *Atlas and Ulbrich* [1977] and *Olsen et al.* [1978]. The scatter around the power law relation between the radar reflectivity factor *Z* (mm^6 m^{-3}) and the rainfall intensity commonly used in radar rainfall estimation (inset in Figure 1) is much larger (a *CV* of the coefficient of 0.27 for all *R* and 0.23 for $R \geq 2$ mm h^{-1}, assuming a fixed exponent of 1.6) than that for the *k-R* relation [see also *Battan*, 1973, Table 7.1, pp. 90–92]. In addition, the nonlinearity of the point-scale *Z-R* relation may cause considerable errors if it is used to estimate volume-averaged rainfall intensities, especially in variable rain. The fact that the *k-R* power law has an exponent that is very close to 1 justifies the use of this point-scale relation to compute line-averaged values of *R* from path-integrated values of *k* (see equation (1)).

2.2. Cellular Communication Links

[8] A set of two nearly parallel operational cellular communication links is located between the towns of Ede and Wageningen, Netherlands. The signal levels of the receivers of these links have been recorded so that rainfall may be estimated from the signal attenuation. The two cellular communication links have one common antenna location (location 0398, see Figure 2), at which the signals are received. The other two antennas transmit at a frequency of 38.530 GHz and are located 7.75 km (antenna 0409) and 6.72 km (antenna 1047) to the south. Instantaneous values of the received signal level are recorded at irregular time intervals and only once or twice every 15 min. The power resolution is 1 dB, which may lead to significant rounding errors in low-intensity events. The transmit powers and radiation patterns of the antennas are not known, and therefore an arbitrary reference level must be chosen. This is done objectively based on the mode of the histogram of the signal power over the full data set (including dry periods). The maximum value that the measured attenuation can attain, and hence the rainfall intensity, depends on the dynamic range of the receiver, the transmit power, the antenna pattern and the length of the link (it decreases as $-20 \log_{10}(L)$ when given in dB). In this case the maximum measurable values of attenuation are 44 dB (link 0409-0398) and 41 dB (link 1047-0398), resulting in maximum measurable path-averaged rainfall intensities of 19.1 mm h^{-1} and 20.5 mm h^{-1}, respectively.

[9] Data have been collected intermittently in the period between 1 September 2003 and 7 December 2003. Unfortunately, no data have been recorded during the most intense events. However, there are several events in the data set suitable for analysis, of which we have selected the eight most intense based on rain gauge and radar measurements.

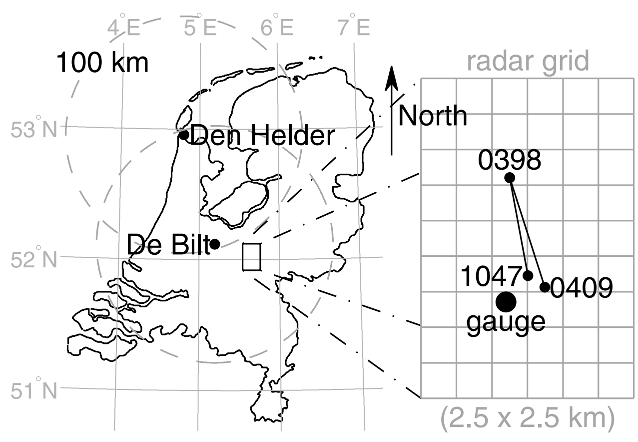

Figure 2. Map of the Netherlands with locations of the antennas of the cellular communication links used (0398, 0409, and 1047), the two KNMI radars at De Bilt and Den Helder and the rain gauge.

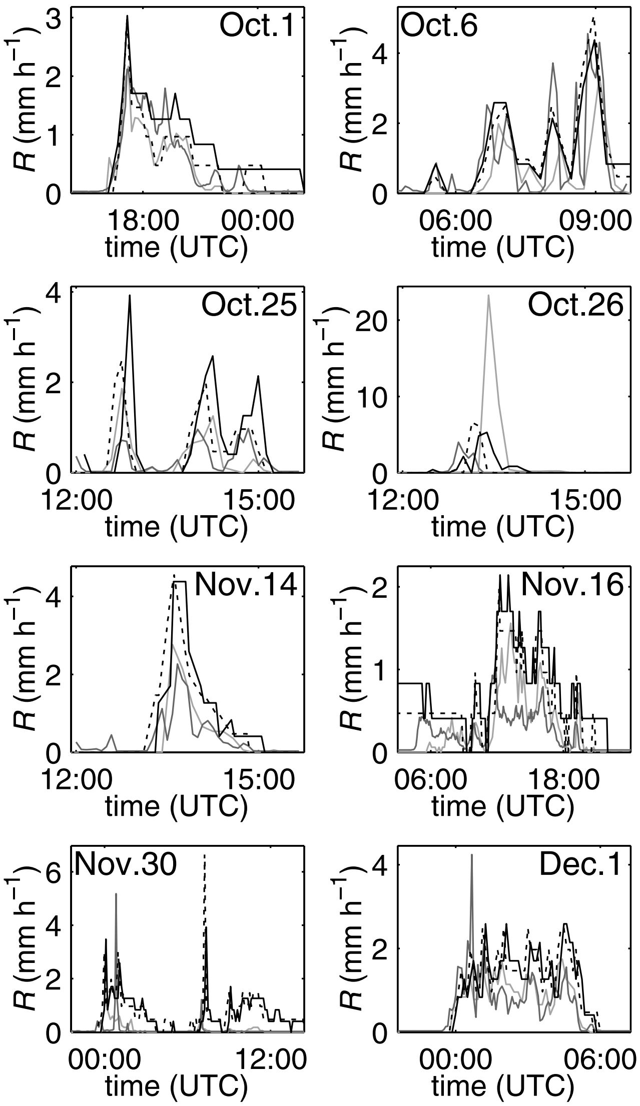

Figure 3. Time series of rainfall intensities estimated by the two links 0409-0398 (solid line) and 1047-0398 (dashed line) and those measured by the rain gauge (light gray line) and the radars (rl, see caption of Table 1, dark gray line) for the eight selected events.

2.3. Rain Gauge and KNMI Radars

[10] We compare the rainfall intensities estimated from the link data with rainfall intensities measured by a nearby rain gauge and a composite of two C band weather radars. The locations of the instruments are shown in Figure 2. The rain gauge located near the two links measures the accumulated rainfall every 10 min by determining the water level in a vessel that is fed by a funnel with an orifice area of 400 cm^2. The accuracy of the gauge is better than 0.03 mm.

[11] The two C band (5.6 GHz) weather radars are operated by the Royal Netherlands Meteorological Institute (KNMI). They are located in De Bilt and in Den Helder (see Figure 2), covering nearly all of The Netherlands. Every 5 min, a map of radar reflectivity factors (Z) is constructed on a 2.5 km by 2.5 km grid. The relation employed to convert Z to R is the one used operationally by KNMI, $R = 0.0365Z^{0.625}$ (i.e., $Z = 200R^{1.6}$ [*Marshall et al.*, 1955]).

3. Results and Discussion

[12] Rainfall intensities that are representative for the two different links are computed from the radar map by weighted averaging of the pixels over the links. The weights are proportional to the distance of a link through the respective radar pixels. Figure 3 shows the comparison of the rainfall intensities measured by the gauge, the radars and those estimated from the signals of both links for the eight events considered. The radar-measured rainfall intensity in Figure 3 is the average of the representative rainfall intensity for both links (rl, see Table 1). The order of magnitude and the dynamics (i.e., the variation with time) of the links, the radars, and the gauge are similar, which is a promising result.

3.1. Statistical Analysis

[13] Table 1 shows the squared correlation coefficients r^2 between the rainfall intensities estimated using the different methods for each of the events. The r^2 values are calculated only with those points where at least one of the variables satisfies $R > 0.0$ mm h^{-1}. It should be noted that when the rain is highly variable in time, slight differences in timing can destroy correlations among signals.

[14] Low values of $r^2_{rg,rl}$ for the comparison of the radar rainfall estimates above the gauge and above the links are indicative of large spatial variations in the rain. Hence, in Table 1 the events are sorted according to increasing spatial variation. An important observation that can be made from Table 1 is that the values of $r^2_{rg,g}$ for the comparison between radar and gauge are lower than those for other comparisons for several events, which may be explained by the large difference in sampling volume, and the significant height of the radar volume above the gauge. This discrepancy can be seen to become larger as the rain becomes more variable. When the spatial variation in rain is small, the links compare better to the gauge, whereas the comparison between the links and the radar is better when the rain is more variable.

Table 1. Squared Correlation Coefficients ($r^2_{\mathrm{x,y}}$) of Comparisons Between Different Methods of Rainfall Intensity Estimation for the Eight Events Sorted According to Decreasing Values of $r^2_{\mathrm{rg,rl}}$, for All the Events Taken Together (Total), and for All Events Except 26 October (Total*)[a]

Event	$r^2_{\mathrm{rg,rl}}$	$r^2_{\mathrm{rg,g}}$	$r^2_{\mathrm{rl1,l1}}$	$r^2_{\mathrm{rl2,l2}}$	$r^2_{\mathrm{g,l1}}$	$r^2_{\mathrm{g,l2}}$	$r^2_{\mathrm{l1,l2}}$
14 Nov	0.75	0.79	0.52	0.67	0.78	0.83	0.96
1 Oct	0.70	0.80	0.82	0.66	0.87	0.84	0.88
16 Nov	0.63	0.43	0.44	0.30	0.64	0.72	0.75
6 Oct	0.46	0.22	0.56	0.55	0.32	0.33	0.94
1 Dec	0.23	0.18	0.25	0.29	0.73	0.71	0.90
30 Nov	0.19	0.02	0.02	0.02	0.27	0.19	0.77
25 Oct	0.09	0.29	0.67	0.55	0.52	0.46	0.75
26 Oct	0.00	0.00	0.35	0.00	0.02	0.01	0.87
Total	0.26	0.04	0.37	0.23	0.09	0.03	0.82
Total*	0.50	0.35	0.37	0.32	0.57	0.48	0.82

[a]See Figure 3 for events. The different methods of rainfall estimation x and y are radar pixel above the gauge (rg), weighted average of radar pixels above link 0409-0398 and above link 1047-0398 (rl1, rl2, respectively), the average of rl1 and rl2 (rl), gauge (g), link 0409-0398 (l1), and link 1047-0398 (l2).

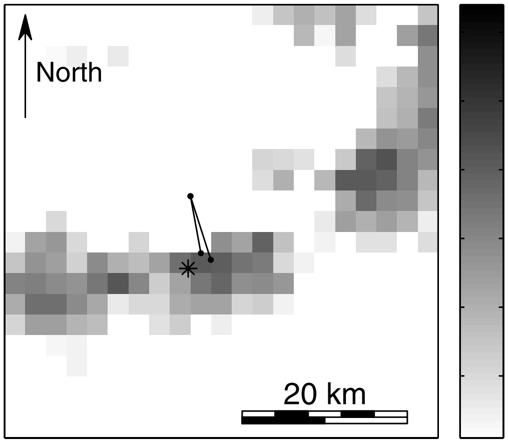

Figure 4. Areal representation of the radar reflectivity factor Z measured by the KNMI radars on 26 October 2003 at 1320 UTC, with the locations of the links and the rain gauge (see Figure 2).

This is because in variable rain the weighted average of the radar pixels above the link provides a better representation of the path-averaged rainfall intensity than the point-scale gauge measurement. The high correlation coefficients of the comparisons between the links and the other instruments for relatively uniform events shows that the dynamics of the rain events is well represented by the links.

[15] The rainfall intensities measured by the two near-parallel links are well correlated, which is to be expected as the measurement principles are the same and their separation in space (antenna locations 0409 and 1047 are 1.44 km apart and the angle between the two links is 7.3°, see also Figure 2) is limited (limiting the differences due to variation in rain). Small differences (up to $\sim$0.5 mm h^{-1}) between the rainfall intensities estimated by the two links may be completely masked by the low (1 dB) resolution of the measurements. The relatively high values of r^2 for the comparisons of the links to other instruments for all of the events except the highly variable event of 26 October shows that cellular communication links are potentially useful for rainfall monitoring.

[16] The event on 26 October 2003 shows large differences between the rainfall intensities measured by the different instruments, both in timing and in magnitude. This event was a convective event, which can generally be characterized by short-duration, high-intensity, and spatially highly variable rainfall. The explanation for the fact that the rain gauge measures much more rainfall than the links can be seen in Figure 4, which shows a map of radar reflectivities measured at the time of the peak of the rain gauge signal (1320 UTC). The rain gauge, located south of the paths between transmitters and receivers of the links, happened to be right in the trajectory of the small but intense rainfall peak.

[17] The fact that the cellular communication links provide relatively direct (due to the near-linear relation) path-averaged estimates of rainfall intensities means that they are much less sensitive to the exact track of the storms than a rain gauge for providing a representative estimate of the rain rate. This is a major advantage of radio links over rain gauges. On the other hand, the low sampling frequency and the limited dynamic range of the links in the present study can cause link estimates of rain accumulation to be less representative for these types of events. For example, a microwave link could miss the most intense part of a convective cell, as the duration of such an event is typically much shorter than the sampling interval used with these links, or the attenuation is so high that the receiver cannot detect the signal. Convective events are the events where radar and link measurements may benefit most from one another. Radar has the advantage of higher spatial resolution, and the links have the advantage of more accurate measurement. In this sense link measurements could provide the correction for radars that rain gauges cannot provide due to their limited sampling area and their sparse density.

3.2. Limitations

[18] It is apparent from Figure 3 that the links overestimate the rainfall intensities in most cases. This may be partly due to the uncertainty in the reference signal level, but is most likely the result of extra attenuation caused by the wetting of the antennas, which can cause several dBs of additional attenuation [*Kharadly and Ross*, 2001]. A correction can be applied when the antennas have been calibrated for this phenomenon [*Minda and Nakamura*, 2005], or if link and gauge or radar data with a sufficient dynamic range are available to calibrate an empirical correction algorithm [*Leijnse et al.*, 2007b]. Unfortunately, neither is the case, so that wet antenna attenuation correction is not possible here.

[19] The effect of the uncertain reference signal level and the rounding error when using a power resolution of only 1 dB can be seen in Figure 5, which shows the effect of shifting the reference signal level by 0.5 or 1 dB (up or down) on the rainfall accumulation for the event of 1 December 2003. The rainfall intensity was set to zero if the estimated attenuation was negative in case of the negative shift of the attenuation. The effect of the shift in the reference signal level is seen to be major, especially for

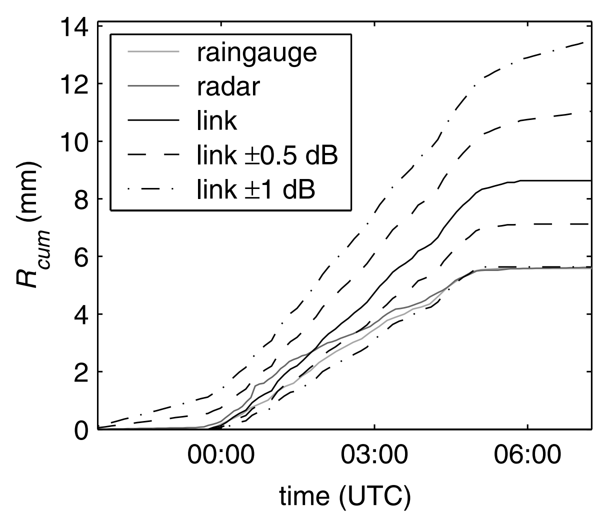

Figure 5. Time series of rainfall accumulation estimated from the link 1047-0398, with offsets in the reference signal level of 0 dB, ±0.5 dB, and ±1 dB, and that measured by the rain gauge (light gray line) and by the radars (dark gray line) for the event on 1 December 2003 (see also Figure 3).

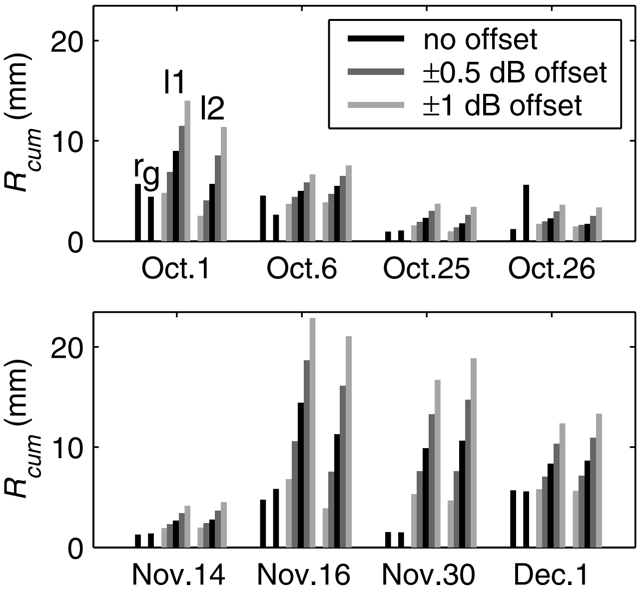

Figure 6. Total rainfall accumulations determined using different methods of rainfall intensity estimation for the eight events (see Figure 3 and Table 1). The different methods of rainfall estimation are weighted average of radar pixels above both links (r), gauge (g), link 0409-0398 (l1) and link 1047-0398 (l2), both with offsets of 0 dB, ±0.5 dB, and ±1 dB.

a long-lasting and low-intensity event like the one under consideration. Had we estimated the reference signal level to be 1 dB higher, the comparison of the link to the gauge and the radars would have been nearly perfect (Figure 5, lower dash-dotted line) in this particular case. Figure 6 shows that the total rainfall accumulations for most of the events considered in this paper computed from the links with a negative offset correspond best to those measured by other instruments. Table 1 also shows the large errors in total accumulation that can occur because of a bias in the received signal level during long events. The consistently better results of the links with a negative offset suggest that there is an additional source of attenuation in rain, most likely the wet antennas.

4. Conclusions

[20] Microwave links such as those employed in cellular communication can potentially be used for the estimation of rainfall. The high density of these links in large parts of the world offers great potential for improving measurements of terrestrial rainfall. Two major reasons why radio links are a useful addition to weather radars for regional rainfall monitoring are (1) that they operate much closer to the ground (tens of meters as opposed to hundreds of meters to kilometers) and (2) that the relation between the observed quantity (rain-induced attenuation) and rain rate shows less scatter and is nearly linear for the employed radio frequencies (in contrast to the highly nonlinear radar reflectivity-rain rate relations). This near-linearity allows for upscaling of point-scale relations without serious problems.

[21] Measurements made in the fall of 2003 with two radio links operated by a commercial cellular communication company have been converted to rainfall intensities using relations derived from electromagnetic scattering laws and drop size distributions that are characteristic for The Netherlands. Comparisons of these rainfall intensities to those measured by a nearby rain gauge and by two C band weather radars have yielded promising results. A statistical analysis shows that in relatively uniform rain, the links compare better to the gauge, whereas in variable rain the comparison between the links and the radar is better.

[22] Before signals measured by cellular communication links can be used to estimate rainfall operationally, several improvements need to be implemented. The reference signal level needs to be known, so that the attenuation can be determined from the deviation of the signal from this level. The very coarse power resolution of the signals that have been used in this paper (similar to that of *Messer et al.* [2006]) may cause large rounding errors, especially in long and low-intensity events. Sampling errors in events that are highly variable in time can easily be overcome by increasing the temporal sampling rate of the links. Finally, the antennas either need to be calibrated for wet antenna attenuation or they need to be shielded from rain.

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