7A.3 IMPROVING RADAR RAINFALL PRODUCTS EMPLOYING DATA FROM CELLULAR TELECOMMUNICATION NETWORKS

Aart Overeem, Wageningen University and Royal Netherlands Meteorological Institute, The Netherlands
Hidde Leijnse, Royal Netherlands Meteorological Institute, The Netherlands
Remko Uijlenhoet, Wageningen University, The Netherlands

1. INTRODUCTION

Microwave links from commercial cellular telecommunication networks may be used for rainfall monitoring, potentially over large parts of the land surface of the earth (Messer *et al.*, 2006; Leijnse *et al.*, 2007a). Along such links, radio signals propagate from a transmitting antenna at one base station to a receiving antenna at another base station. Rain-induced attenuation and, subsequently, path-averaged rainfall intensity can be retrieved from the signal's attenuation between transmitter and receiver (Figure 1).

Recently, Overeem *et al.* (2013) have shown that country-wide rainfall maps can be obtained from microwave link data for The Netherlands (38,000 km^2). Rainfall maps solely based on received signal levels compare quite well with those based on gauge-adjusted radar data for a 12-day validation dataset. Hence, rainfall estimation using microwave links holds a promise, although more research is needed to obtain accurate rainfall maps all year round, i.e., to develop a real-time application.

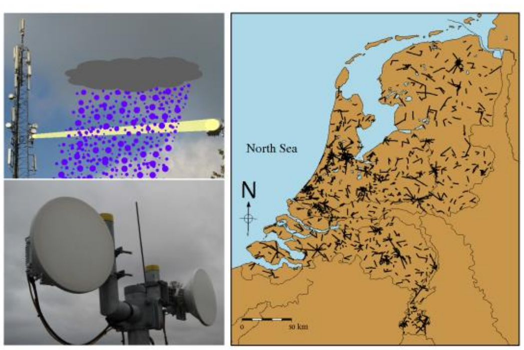

Figure 1: Photographs and locations of commercial microwave links in The Netherlands.

For countries operating weather radars a potential benefit of link rainfall data lies in merging with radar rainfall data. Upton *et al.* (2005) suggest to correct for attenuation in real-time radar rainfall images by employing microwave links. Krämer *et al.* (2005) use an experimental microwave link to correct X-band radar data for attenuation. Cummings *et al.* (2009) investigate the use of two experimental microwave links to adjust the radar rainfall field, and Overeem *et al.* (2012) present one daily link-adjusted radar rainfall map, where received signal levels from 321 commercial microwave links have been employed.

Often radar rainfall images are adjusted employing rain gauge data to improve the quality of rainfall maps. However, the number of automatic rain gauges suitable for adjustment is generally low, thus limiting the improvement of real-time radar rainfall images of, e.g., 1-hour rainfall depths. In general, the number of microwave links in a country will be much larger than the number of (automatic) rain gauges. For example, the Royal Netherlands Meteorological Institute (KNMI) operates 32 automatic rain gauges in The Netherlands (1 gauge per 1000 km^2), whereas data from 1500 link paths are available. Microwave links are not expected to be as accurate as rain gauges, but their large number may partially compensate for this. Adjustment of radar data utilizing microwave link data could substantially improve the quality of real-time radar rainfall products and thus increase their applicability for hydrological purposes, validation of precipitation forecasts of numerical weather prediction models, as well as validation of satellite-based rainfall retrievals.

The potential of microwave link data to improve real-time radar rainfall products is investigated. A dataset from a commercial microwave link network over The Netherlands is analyzed, containing data from an unprecedented number of links (~ 1000-1500) covering the land surface of The Netherlands (38000 km^2). This dataset spans from January 2011 through October 2012. Three-hour rainfall accumulations are derived from the microwave link data and

Corresponding author address: Aart Overeem, Hydrology and Quantitative Water Management Group, Wageningen University, P.O. Box 100, 6700 AC, Wageningen, The Netherlands; e-mail: aart.overeem@wur.nl

employed to adjust country-wide maps of three-hour radar rainfall accumulations. These adjusted maps are then accumulated to daily rainfall maps. The 3-h and daily rainfall maps are verified against a high-quality, climatological, gauge-adjusted radar rainfall dataset and are also compared to the existing real-time radar rainfall product which has been obtained by adjustment with data from 32 automatic rain gauges.

2. DATA

2.1 *Commercial microwave link data*

Received signal level data were obtained from typically 1000-1500 microwave link paths of a cellular telecommunication network in The Netherlands, which have an average length of about 3 km. Figure 1 (right) shows the distribution of selected microwave links over the country. The available data are minimum and maximum powers over 15-min intervals with a precision of 1 dB, based on 10-Hz sampling.

2.2 *Rain gauge data*

The KNMI automatic rain gauge network consists of 32 rain gauges (~ 1 station per 1000 km^2). These electronic rain gauges measure the precipitation depth by using the displacement of a float placed in a reservoir. Interpolated (using ordinary Kriging) maps of 3-h and 24-h rainfall accumulations are obtained from the rain gauge data. KNMI also operates a network of manual rain gauges that is much denser (1 per 100 km^2), but these gauges report only once per day. Data from this network are used to adjust daily radar rainfall accumulations.

2.3 *Radar rainfall datasets*

A radar dataset of path-averaged rainfall intensities over each link was constructed, to serve as a reference in the calibration of the rainfall retrieval algorithm. Gauge-adjusted radar data were obtained, following a similar procedure to that in Overeem *et al.* (2009a,b). Horizontal cross sections of the radar reflectivity factor at constant altitude (pseudo-CAPPI images) of 1500 m were utilized with a 5-min temporal and a 1-km spatial resolution. This composite was based on data from the two C-band Doppler weather radars in The Netherlands. After ground clutter removal, the reflectivity factors were converted to rainfall intensities using a fixed *Z-R* relationship. Rain gauge networks were employed to adjust the radar data. A daily spatial adjustment, using daily rain gauge rainfall depths (~1 station per 100 km^2), was combined with an hourly mean-field bias adjustment, using hourly rain gauge rainfall depths (~1 station per 1000 km^2). For a more elaborate description of the radar data and the employed adjustment methods, see Overeem *et al.* (2009a,b). In this study, this climatological radar rainfall dataset is considered as ground-truth and is used to verify rainfall maps.

Subsequently, path-averaged rainfall intensities were derived for each link and 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. Daily rainfall depths were calculated from these mean 15-min radar rainfall intensities. In a similar way, these mean 15-min rainfall intensities were also derived for the unadjusted radar data, where no rain gauges were used to adjust the data (comparable to operational radar rainfall intensities).

KNMI employs a mean-field bias adjustment to adjust 3-h radar rainfall accumulations every hour (using a moving window) by using 3-h rainfall depths from 32 automatic rain gauges (Holleman, 2007). This operational radar rainfall product is, e.g., used by water authorities. A mean-field bias adjustment method has been or is utilized in many countries for operational radar rainfall products.

3. METHODOLOGY

3.1 *Rainfall estimation from microwave links*

Several sources of error have been encountered in estimation of rainfall intensities using microwave links (see, e.g., Leijnse *et al.*, 2007b, 2010). Signal losses not related to rainfall often occur and need to be removed. In this study radar data are used to identify wet and dry spells (called the radar approach). 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 steps are classified as wet. The subsequent time step is included, because the radar measures at larger heights and it therefore takes some time for hydrometeors to reach the earth's surface. Apart from this, exactly the same methodology is followed as described in Overeem *et al.* (2013). Minimum and maximum received powers are converted to maximum and minimum attenuation, respectively. A filter is used to remove outliers in attenuation. The climatological radar dataset has been used to calibrate the microwave link rainfall retrieval algorithm. The path-averaged mean 15-min rainfall intensity is computed from the minimum and maximum attenuation, whereby a simple correction algorithm for wet antennas is employed. The optimal values of the two parameters in the retrieval algorithm are taken from Overeem *et al.* (2013), where these were based on 12 days. These days are excluded from the microwave link dataset which spans from January 2011 till October 2012. For each available 15-min period 15-min rainfall intensities are calculated from the microwave link data resulting in a dataset of 623 days.

3.2 Link-adjustment of radar-based rainfall accumulations

Often a mean-field bias adjustment is applied to adjust radar data employing rain gauge data. This implies that for every time step an adjustment factor is calculated which is constant for every pixel in the radar image. Since radar precipitation estimates often deteriorate for increasing distance to the radar, a local adjustment factor would be more appropriate. However, the often low density of automatic rain gauge networks is expected to limit the possibilities of such a local adjustment. For example, in The Netherlands KNMI operates one automatic rain gauge per 1000 km^2. The number of microwave links is often much larger than the number of automatic rain gauges. In this study data from typically 1000-1500 microwave links are available compared to data from 32 automatic rain gauges. Hence, a spatial adjustment is applied in order to locally adjust radar data for it's often spatially dependent (sources of) error.

Link-based 3-h rainfall accumulations are used to adjust the raw radar composite of 3-h rainfall depths. Link rainfall depths are considered as point measurements. A spatial adjustment of unadjusted radar composites is performed using a modified version of the Barnes adjustment, which is described in Overeem *et al.* (2009a). The spatial adjustment factor F_S^c is a distance-weighted interpolation (Barnes, 1964) of the ratio of the microwave link rainfall depths and the corresponding raw radar precipitation depths at the location of the middle of the link:

$$F_S^c(i,j) = \frac{\sum_{n=1}^{N} w_n(i,j) \times M(i_n, j_n)}{\sum_{n=1}^{N} w_n(i,j) \times R_{raw}(i_n, j_n)} ,$$

where the subscript *S* denotes the spatial adjustment method, *N* is the number of radar-link pairs, and $w_n(i,j)$ is a weighting function, given by:

$$w_n(i,j) = \exp\left[-d_n^2(i,j)/\sigma^2\right] ,$$

where σ (10 km) determines the smoothness of the F_S^c field and $d_n(i,j)$ is the distance between the middle of link *n* and radar pixel (i,j). The composite of unadjusted accumulated precipitation from the radars is adjusted for each 3 hours as:

$$R_S^c(i,j) = R_{raw}(i,j) \times F_S^c(i,j) .$$

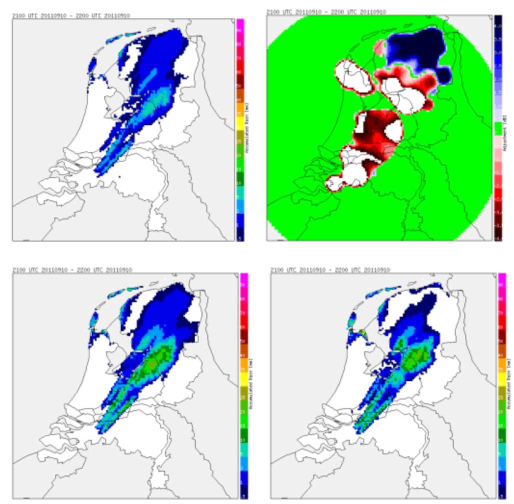

Figure 2: Hourly rainfall accumulations from radars (unadjusted; left upper panel), radars + gauges (ground truth; left bottom panel), radars + links (right bottom panel). The spatial adjustment factor field is also shown (upper-right panel).

Figure 2 gives an example of a link-adjusted radar rainfall image. The link-adjusted radar rainfall map corresponds quite well to the radar ground-truth, although an underestimation is found in the northeastern part of the country. In general, the large underestimation found in the unadjusted radar rainfall image is successfully removed.

4 RESULTS

4.1 *Scatter density plots of daily rainfall*

The 3-h operational radar rainfall product and the 3-h link-adjusted radar rainfall maps are accumulated to daily rainfall maps and compared to the climatological radar rainfall dataset ("ground truth"). For all daily scatter density plots only those pixels are used where one or both observational systems have measured > 1 mm. The daily unadjusted radar rainfall maps (Figure 3) reveal a severe underestimation of almost 50%. The link-adjusted radar rainfall dataset effectively removes this underestimation and increases the coefficient of determination ρ^2 (i.e., the fraction of explained variance) by 0.1 (Figure 4). The coefficient of variation CV (i.e., the ratio of the standard deviation

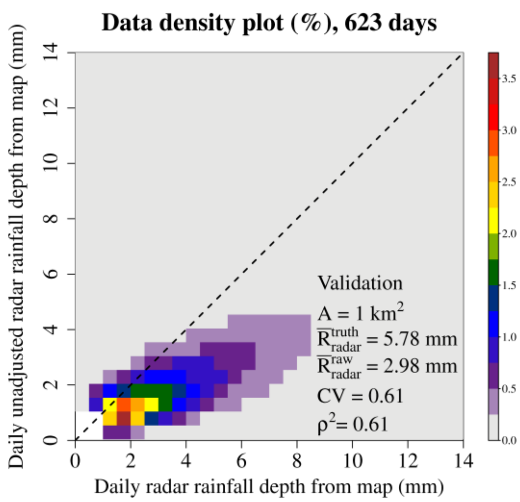

Figure 3: Verification of daily rainfall maps from unadjusted radar data against those from gauge-adjusted radar rainfall data ("ground-truth").

of the differences to the mean radar rainfall depth) is similar. This shows that adjustment using microwave links clearly improves unadjusted radar rainfall maps.

Figure 5 reveals that the underestimation is largely removed for the gauge-adjusted operational radar rainfall product, although an underestimation of 12% is found, which can partly be explained by systematic differences between depths from automatic and manual rain gauges. In terms of CV and ρ^2, the operational rainfall product is better than the link-adjusted radar rainfall dataset.

Despite the fact that a spatial adjustment is used instead of a simple mean-field bias adjustment and despite the number of microwave links being much larger than the number of automatic rain gauges.

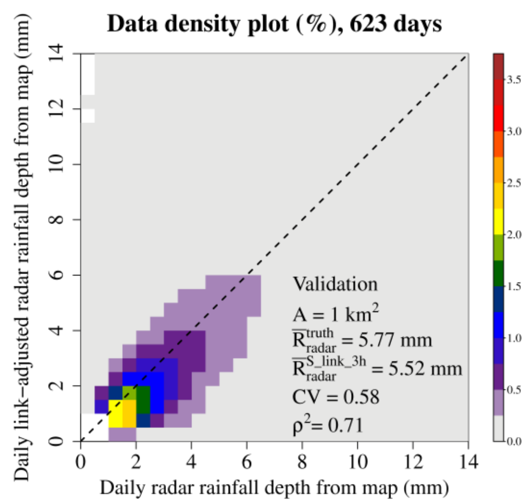

Figure 4: Verification of daily rainfall maps from link-adjusted radar data against those from gauge-adjusted radar rainfall data ("ground-truth")

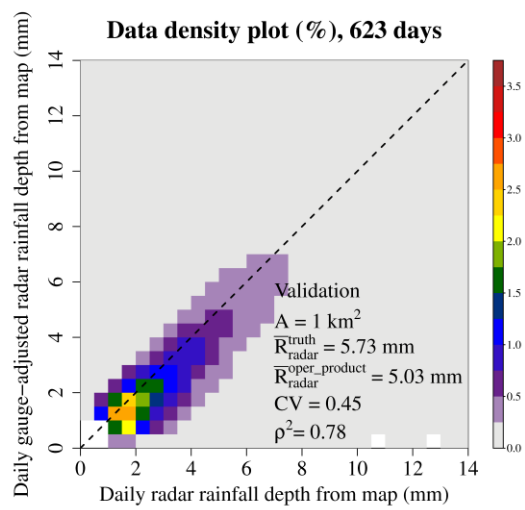

Figure 5: Verification of daily rainfall maps from operational gauge-adjusted radar rainfall product against those from gauge-adjusted radar rainfall data ("ground-truth")

Finally, Figure 6 shows the results for the interpolated maps of automatic rain gauge data. Performance is similar to the link-adjusted radar rainfall product.

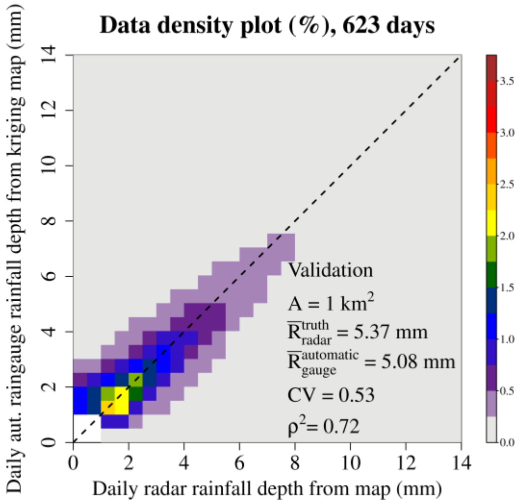

Figure 6: Verification of daily rainfall maps from automatic rain gauge data against those from gauge-adjusted radar rainfall data ("ground-truth").

4.2 *Scatter density plots of 3-h rainfall*

The requirements for the number of observations in space will generally increase for shorter durations due to the larger spatial rainfall variability. Again the link-adjusted radar rainfall data and the interpolated automatic rain gauge data are compared to the radar ground truth, but now for a duration of 3 hours. According to Figures 7 and 8 the link-adjusted radar rainfall product clearly outperforms the interpolated rainfall maps based on automatic rain gauge data, as can particularly be seen from the value of ρ^2. This confirms that link-adjusted radar rainfall maps can especially yield additional information for sub-daily durations.

5 CONCLUSIONS AND DISCUSSION

Results confirm the potential of microwave links for adjustment of radar rainfall accumulations employing a dataset of unprecedented length (623 days). The bias in unadjusted radar rainfall images is effectively removed. However, on a daily time scale, KNMI's real-time operational 3-h radar rainfall product is still better than the envisaged 3-h link-based radar rainfall product. Apparently, the large number of microwave links and the spatial adjustment is not enough to compensate for the lower quality of link-based rainfall estimates. A simple mean-field bias adjustment using a low number of, although more accurate, automatic rain gauge data gives better results. Nevertheless, if no or hardly any automatic rain gauges would be available, a link-based radar rainfall product could already be valuable.

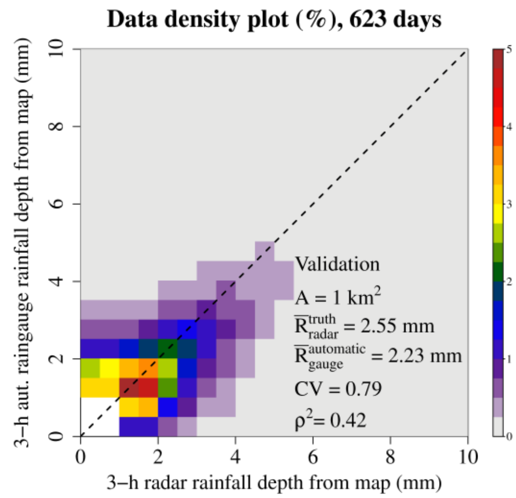

Figure 7: Verification of 3-h rainfall maps from automatic rain gauge data against those from gauge-adjusted radar rainfall data ("ground-truth").

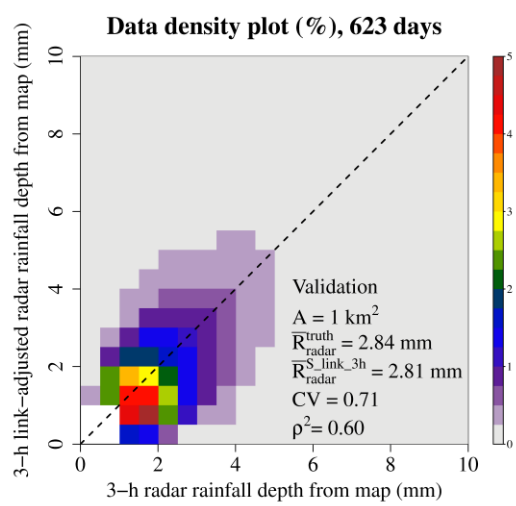

Figure 8: Verification of 3-h rainfall maps from link-adjusted radar data against those from gauge-adjusted radar rainfall data ("ground-truth")

The spatial adjustment using microwave link data has also been performed on 1-h unadjusted radar rainfall maps. Verification of daily rainfall maps showed that similar results were found as for the 3-h spatial adjustment. Hence, a 1-h link-adjusted radar rainfall product may even be of sufficient quality, despite timing differences between both observational systems (e.g., due to the often large height of the middle of the radar beam above the earth's surface).

The scatter density plots provide valuable information on the performance of all (combinations) of observational systems. Clearly more measures of fit and verification methods need to be employed in order to better assess the quality of rainfall maps.

Verification should also be performed on shorter time scales. In particular, the 3-h (and possibly 1-h) link-adjusted radar rainfall accumulations should be compared to the operational 3-h gauge-adjusted radar rainfall product. It should be noted that the climatological radar dataset is assumed to be the ground-truth, but also has its limitations, particularly for shorter durations such as 3 hours.

The microwave link rainfall estimates are assigned to the middle of the link, i.e., path measurements are assumed to represent point measurements. In addition, the corresponding radar rainfall depth at that particular location has been selected for the adjustment. I.e., the path-averaged, unadjusted radar rainfall intensity is not used for that purpose, because it differs from the unadjusted radar rainfall image which needs to be adjusted, due to a different processing. The path-averaged character of microwave link observations should preferably be taken into account in follow-up studies. Path (microwave links) and volume (radar) measurements need to be combined in an optimal manner, which requires the development of new geostatistical methods. Further, the used spatial adjustment is only one out of many possible methods to adjust radar data, and not necessarily the best.

Despite these and other shortcomings and the operational gauge-adjusted radar rainfall product still being better than the envisaged link-adjusted one on a daily scale, merging link and radar data is promising given the omnipresence of cellular telecommunication networks worldwide. The rainfall retrieval algorithm has been applied to 623 days from all seasons, whereas the optimal parameters have been taken from Overeem *et al.* (2013), being optimized for June and July 2011 (summer). Different values of these coefficients may be more appropriate for other seasons and may improve results. In addition, microwave links are especially suitable for rainfall estimation, and not for solid precipitation. Although solid or freezing precipitation constitutes on average only 7% of the total time of precipitation in The Netherlands, this will have negatively influenced the results shown in this paper. In general, much more research is needed in order to identify and correct for errors in link-based rainfall estimates. This implies that link-based rainfall estimates and, hence, link-adjusted radar rainfall maps may further improve.

Acknowledgments

We gratefully acknowledge Ronald Kloeg and Ralph Koppelaar from T-Mobile NL for providing the cellular telecommunication link data. This work was financially supported by The Netherlands Technology Foundation STW (project 11944).

REFERENCES

Barnes, S. L., 1964: A technique for maximizing details in numerical weather map analysis. *J. Appl. Met.*, 3, 396–409.

Cummings, R.J., Upton, G.J.G., Holt, A.R. & Kitchen, M., 2009: Using microwave links to adjust the radar rainfall field. *Adv. in Water Res.*, 3, 396–409, doi: 10.1016/j.advwatres.2008.08.010.

Kramer, S., Verworn, H.-R. & Redder, A., 2005: Improvement of X-band radar rainfall estimates using a microwave link. *Atmospheric Research*. 77, 278-299, 10.1016/j.atmosres.2004.10.028.

Leijnse, H., Uijlenhoet, R. & Stricker, J.N.M., 2007a: Rainfall measurement using radio links from cellular communication networks. *Water Resour. Res.*, 43, doi:10.1029/2006WR005631.

Leijnse, H., Uijlenhoet, R. & Stricker, J.N.M., 2007b: Hydrometeorological application of a microwave link: 2. Precipitation. *Water Resour. Res.*, 43, doi:10.1029/2006WR004989.

Leijnse, H., Uijlenhoet, R. & Berne, A., 2010: Errors and uncertainties in microwave link rainfall estimation explored using drop size measurements and high-resolution radar data. *J. Hydrometeor.*, 11, doi: 10.1175/2010JHM1243.1.

Messer, H.A., Zinevich, A. & Alpert, P., 2006: Environmental monitoring by wireless communication networks. *Science*, 312, 713.

Overeem, A., Holleman, I. & Buishand, A., 2009a: Derivation of a 10-year radar-based climatology of rainfall. *J. Appl. Met. Clim.*, 48, 1448, doi:10.1175/2009JAMC1954.1.

Overeem, A., Buishand, A. & Holleman, I., 2009b: Extreme rainfall analysis and estimation of depth-duration-frequency curves using weather radar. *Water Resour. Res.*, 45, doi:10.1029/2009WR007869.

Overeem, A., Leijnse, H. & Uijlenhoet, R., 2012: Quantitative precipitation estimation using commercial microwave links. In: *Weather Radar and Hydrology, Proceedings of a symposium held in Exeter, UK, April 2011*, 129-134. Editors: R. J. Moore, S. J. Cole & A. J. Illingworth. IAHS Publ. 351, IAHS Press, Wallingford, Oxfordshire, U.K.

Overeem, A., Leijnse, H. & Uijlenhoet, R., 2013: Country-wide rainfall maps from cellular communication networks. *Proc. Nat. Acad. Sciences*, 110, 2741-2745, doi:10.1073/pnas.1217961110.

Upton, G.J.G., Holt A.R., Cummings, R.J., Rahimi, A.R. & Goddard, J.W.F., 2005: Microwave links: The future of urban rainfall measurement? Atmospheric Research, 77, 300-312, doi:10.1016/j.atmosres.2004.10.009.