TOWARDS THE USE OF X-BAND DUAL POLARIMETRIC RADAR RAINFALL ESTIMATES IN URBAN HYDROLOGY

by

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ABSTRACT

Cities' vulnerability to extreme rainfall is increasing due to urbanization, increase of imperviousness, implementation of complex network of infrastructures, and alteration of precipitation patterns as an effect of climate change. More severe and more frequent storms are expected, having a strong impact in urban catchments, which will become more prone to floods. Because of the short duration and rapid variation in intensity especially of summer storms, there is a strong need of both spatial and temporal high resolution rainfall measurements or estimates. Moreover, urban hydrological modelling requires high resolution rainfall data to be able to simulate fast runoff processes and related short response times. This can be provided by X-band radars. In this work, data from IDRA, the dual- polarimetric X-band radar at the Cabauw Experimental Site for Atmospheric Research (CESAR, Cabauw, the Netherlands) are presented, based on a particular rainfall rate retrieval that is independent of the absolute radar calibration and not affected by attenuation as long as the radar signal is not totally extinct. The results show a comparison between three different sources of rainfall data, demonstrating the higher spatial variability of X-band radar data compared to rain gauge and C-band radar data. A first attempt is made to analyse and explain deviations between the rainfall data sources.

Keywords: Radar data, spatial variability, X-band radar, C-band radar, rainfall retrieval, differential phase

1 INTRODUCTION

Usually pluvial floods in cities occur due to extremely intense precipitation, with rainfall intensities typically higher than 20 mm/h and storm durations of a few hours. Since urban catchments are much smaller and more impervious than rural ones, the hydrological response is faster. In this context, rainfall information, which is the main input of hydrological models, is a critical component to effectively model urban drainage systems.

Traditionally rainfall measurements were obtained by rain gauges, which provide accurate estimations at ground level. However, rain gauge provides point measurements that cannot give information about the variability of rainfall over an area (Krajewski et al., 2003). Recently, radar estimations have been taken into account, since they are able to describe the spatial variation of rainfall during a storm. Weather radars, such as S-band and C-band radars, are already used by meteorological institutes all over the world in order to (indirectly) measure and predict precipitation at national and regional scales. Nonetheless, several studies have shown that the spatial resolution of the operational radar network measurements is still insufficient to meet the relevant scale of urban hydrodynamics (Berne et al., 2004; Emmanuel et al., 2011; Schellart et al., 2011). The results of these studies have highlighted the need to measure rainfall at higher spatial and temporal resolutions. Because of their relatively low cost and small size, X-band radars are ideally suited for local rainfall estimation. This results in high resolution in both space and time, and in measurements that are generally much closer to the ground than those of operational S- or C-band radars. Such local X-band radars have been tested and seem to show a better performance in catching the rapidly changing characteristics of intense rainfall than rain gauges (Jensen and Pedersen, 2005), especially when the distance between rain gauges is higher than 3-4 km (Wood et al., 2000).

Most X-band radars currently in use are non-polarimetric; the rainfall rate is usually determined via a relation with the reflectivity (Z-R relation). Unfortunately, the reflectivity measurement is strongly affected by radar attenuation, especially during high intensity rainfall and a small error of the measured reflectivity results in a large error of the estimated rainfall rate. One possible way to cope with this is to use polarimetric radars with linear horizontal and vertical polarization (Otto and Russchenberg, 2011). These kinds of radars measure the differential phase (i.e., the phase difference between the co-polarized echoes at horizontal and vertical polarization), which is found to be independent of the absolute radar calibration and not affected by attenuation as long as the radar signal is not totally extinct.

The present paper compares X-band radar rainfall estimates, retrieved by means of the differential phase method, to both C-band radar rainfall estimates and traditional ground measurements provided by rain gauges. The study is conducted in the Netherlands, where the three types of rainfall measurements are available. Furthermore, the study analyses the spatial variability sampled by X-band radar at scales relevant for urban areas. The analysis shows that its high resolution exhaustively reproduces the temporal and spatial evolution of a rapidly changing storm in an urban area, but also highlights the large deviation of both radar data from rain gauge ones, and raises issues to be further investigated in order to use the radar product for urban hydrology applications.

2 DATA SET

2.1 Experimental site

The rainfall measurements analysed in this study were taken at the CESAR site (Cabauw Experimental Site for Atmospheric Research). CESAR is a consortium of three universities and five major research institutes, hosting several instruments that measure rainfall with different spatial and temporal scales (Leijnse et al., 2010). The site is located between the villages of Cabauw and Lopik, the Netherlands, and is operated by the KNMI (Koninklijk Nederlands Meteorologisch Instituut). One of the four radars available at CESAR is IDRA, a dual-polarimetric X-band radar operated by Delft University of Technology (TU Delft). The radar is located on top of a 200 m tower, and scans at 1 rpm at an elevation angle of 0.5º. Radar data are processed in real-time applying a spectral polarimetry algorithm (Unal, 2009) in order to suppress clutter and hence to improve precipitation observation. Once pre-processed, radar data are transformed into rainfall rate, by means of two different retrieval methods: the specific differential phase (K_{dp}) and the reflectivity at horizontal polarization (z_{hh}), as follows:

$$z_{hh} = 243 \cdot R^{1.24} \tag{1}$$

with the rainfall rate R (mm h^{-1}) and the reflectivity at horizontal polarisation z_{hh} ($mm^6\, m^{-3}$)

and

$$R = 13 \cdot K_{dp}^{0.75} \tag{2}$$

with the rainfall rate R (mm h^{-1}) and the one-way specific differential phase K_{dp} (deg km^{-1}).

Equation (1) is the 'Z-R' relationship, which is an empirical relationship dependent on the drop size distribution (DSD) of rainfall, widely used by radar meteorologists (Villarini and Krajewski, 2010).

Equation (2) retrieves rainfall through the specific differential phase K_{dp}, which is the reflectivity-weighted to overcome the coarse range-resolution of conventional K_{dp} estimators; the estimated K_{dp} is unaffected by signal attenuation and independent of the radar calibration (Otto and Russchenberg, 2011). According to Otto and Russchenberg (2011), R (K_{dp}) is chosen for the final rainfall rate product if the reflectivity is above 30 dBZ and the standard deviation of K_{dp} is below 2 deg km^{-1}, otherwise R (z_{hh}) is used.

Data were obtained from IDRA and also from weighted average of two C-band radars belonging to the operational weather radar network of the Netherlands, operated by KNMI, according to KNMI protocol (Overeem and Holleman, 2010). One of them is located in De Bilt, close to the city of Utrecht, and the other one in Den Helder, in the northern part of the country. Both radars scan at beam elevation angles of 0.3º, 1.1º, 2.0º and 3º. More characteristics of X-band and C-band radar are listed in *Table I*.

The rainfall reference value was taken by the dense rain gauge network located around the CESAR site. The network includes 6 tipping-bucket rain gauges with a volumetric resolution of 0.2 mm, and has a radius of approximately 10 km, with a maximum distance between gauges of 15 km. It is located around the CESAR site.

In order to determine the spatial variability of the precipitation and to compare the performance of the three instruments (i.e., X-band radar, C-band radar and rain gauges), small areas centred in the 6 rain gauge locations were selected and radar rainfall estimates of those areas were compared to rain gauge measurements. Each one of the six areas is about 1 km²; the size of the areas was chosen especially to represent the typical extent of a hypothetical sewer district, representative of sewer districts in the nearby city of Utrecht. Thus, for each one of them, 167 X-band rainfall time series were available (i.e., the area is covered by 167 X-band pixels of spatial resolution of 100 x 100 m) and a certain number (depending on the location) of C-band pixels of 1 km spatial resolution, as it is shown in *Figure 1*.

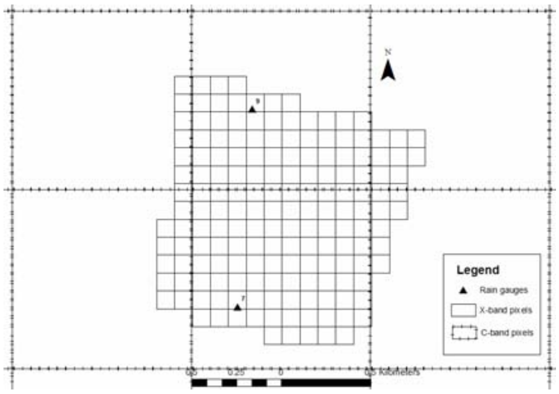

Figure 1 – Example of the study area: the study compares rain gauge measurements (black triangles) with radar estimates of the overlapping pixels (small and big grids, see legend).

The temporal resolution of the data was 5 minutes, which is the operational resolution of the national C-band radar network. The rain gauge and the X-band (originally 1 minute) resolutions were aggregated to the C-band one, in order to be comparable. One intense rainfall event was selected for analysis; specifications of the event are reported in *Table II*. The event occurred between 1 a.m. and 3 a.m. on 26th of May 2009, the last year the rain gauge network was operative.

Table I – Specifications of available radars: X-band radar and C-band radar.

Specifications	X-band radar	C-band radar
Frequency	9.475 GHz	5.6 GHz
Polarization	dual polarization	horizontal
Spatial resolution	100 m	1 Km
Temporal resolution	1 min	5 min
Beamwidth	1.8°	1°
Elevations	0.5°	0.3°-3°

3 METHODOLOGY

Rain gauge measurements and radar rainfall estimates of the pixels overlapping rain gauge locations were compared using Pearson correlation coefficient and Nash criterion. Pearson coefficient shows whether both variables follow the same trend; Nash criterion is commonly used in hydrology to assess the goodness of a prediction compared to the observed value (see also Krause et al., 2005). Here it is used to assess the performance of radar estimations (assumed to be the modelled values) with respect to rain gauge measurements (taken as reference value).

4 RESULTS AND DISCUSSION

Results of the statistical comparison are given in *Table II; Figure 2* presents a scatter plot of the data and in order to quantify the linear data correlation, the slope was computed.

According to Pearson coefficients (*Table II*), both C-band and X-band radar data have a positive correlation with rain gauge data at all the locations. Values range from 0.52 to 0.96 for C-band-rain gauge correlation and are slightly lower (0.26-0.75) for the pair X-band-rain gauge. As expected (Bruni et al., 2012), rain gauge measurements show higher rainfall values with respect to both X-band and C-band radar estimates;

rain gauge rainfall peaks are up to three times higher than radar estimates. The weak estimated rainfall rates by IDRA may be partially attributed to the signal processing which was until the end of 2009 optimised for the observation of weak echoes such as drizzle and low-level clouds. Strong echoes, e.g. by heavy precipitation, were partially suppressed. According to Nash criterion, X-band estimates were accurate in gauge 5, 6 and 7 (positive values); C-Band estimates match reasonably well rain gauge measurements in gauge 4, 5, 6, 7, and 12 . However, Nash coefficient is close to zero, which means that estimates are accurate with respect to the mean of rain gauge measurements, while radar estimates fail to represent the temporal variability of the rainfall. At rain gauges 4 and 5 (*Figure 3*), both radar estimates are lower than rain gauge measurements, as well as the peaks are shifted on time. This mismatch of peak intensity and time-to-peak can be explained by the time it takes raindrops to fall from 1500 m altitude to the ground, in combination with the 'shift' caused by the wind on the rain in the atmosphere, and the time resolution of the C-band radar. A shift in time can have a strong negative effect on correlation coefficients. Regarding the wind effect, assuming that the averaged wind velocity is 10 m/s, which is not uncommon during extreme rainfall events, the rain would be drifted several hundred meters for IDRA and more than 1 km for the operational C-band radar when it reaches the ground. As a consequence, what is measured by the radar in the air might not correspond to what is measured at ground level, given the same location of rainfall observation. A second aspect to take into account is that the radar data are snapshots in time (i.e., 1 minute for IDRA and 5 minutes for C-band radars), whereas the rain gauge data are time-averages. If the rainfall front travels at 10 m/s, it has travelled 600 m in 1 minute and 3 km in 5 minutes, which is six X-band radar cells and three C-band radar cells respectively. In variable rain such as the event considered in this study, this can cause errors because the radar might miss the most intense peak of an event at a given location, if it is not measuring at that location when the peak passes over. This problem can be solved by interpolating subsequent measurements or by averaging the data in space, although in the latter case the spatial variability information needed to better describe the rapidly changing characteristics of the rainfall event would be lost.

Table II – Statistical characteristics of the comparison between the radar estimates and the rain gauges (slope of the regression line, Pearson correlation coefficient, Nash criterion and total rainfall volume).

	Slope CB-RG	**Slope XB-RG**	**Pearson CB-RG**	**Pearson XB-RG**	**Nash CB-RG**	**Nash XB-RG**	**Total rainfall volume (mm)**		
							RG	**XB**	**CB**
Gauge 12	3.42	5.36	0.65	0.26	0.05	-0.22	327.6	27.2	81.5
Gauge 13	0.35	1.77	0.52	0.59	-4.22	-0.47	77.0	24.8	69.1
Gauge 9	1.4	2.48	0.55	0.47	0.13	-0.05	211.5	61.9	82.1
Gauge 7	1.42	1.94	0.66	0.71	0.21	0.22	182.0	79.5	74.5
Gauge 5	1.85	2.02	0.70	0.75	0.22	0.27	227.3	96.0	83.2
Gauge 6	1.31	2.51	0.54	0.64	0.07	0.06	234.1	75.7	81.8
Gauge 4	1.26	2.67	0.88	0.09	0.68	-0.39	248.1	34.5	146.8

While radar data values may deviate strongly from rain gauge data, spatial distribution of rainfall provided by radars is still a gain when a detailed spatial description of the storm over an area is needed. Finer temporal resolution is also needed, since extreme storms intensity varies rapidly any minute, as *Figure 2* shows. The latter displays five subsequent minutes of X-band measurements: location and intensity of the storm vary considerably. This cannot be caught either by C-band radar (due to the coarse spatial and temporal resolutions) or rain gauges (since they measure at one location). Within the duration of five minutes C-band radar performs only one scan and gives one rainfall value averaged over the whole area, while rain gauges measure the rain fallen in the two black triangles; at those locations rainfall is quite uniform and less than 20 mm/h (except minute 1 and minute 5), which does not represent the intensity of the storm.

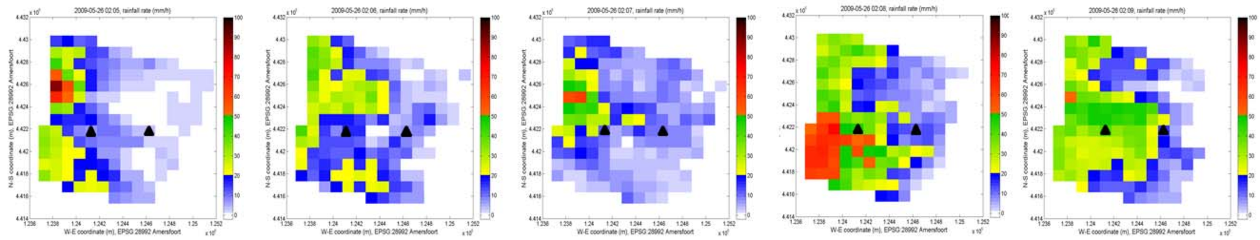

Figure 2 – X-band rainfall estimations and rain gauges (black triangles) locations: 26th of May 2009, from 02:05 to 02:09.

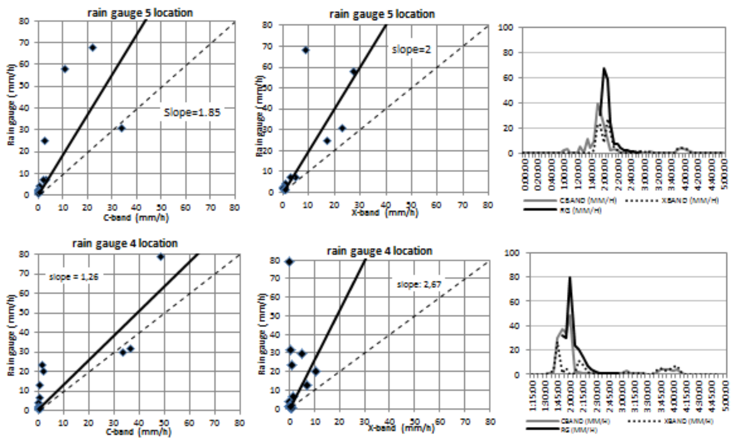

Figure 3 – Scatter plots and rainfall trend (mm/h over time) of May 2009 at locations 4 and 5: C-band and X-band estimates against rain gauge measurements.

5 CONCLUSIONS

This study compared rain gauge rainfall measurements with C-band and dual-polarimetric X-band radar estimates in order to assess and explain deviations between these measurements and possible implications for analyses at the urban scale. Both radars underestimated rainfall peaks when compared to rain gauge measurements, and did not accurately match times-to –peak. This was attributed to the effect of the wind and the different way of measuring: rain gauges are time averaged measurements while radar estimates are snapshot each given time range. However, spatially distributed information provided by the radar grids, especially high resolution X-band radar data, is crucial to comprehensively describe rapidly changing storms over small areas such as urban catchments. Further research has to be done in order to include wind effect and thus to estimate the exact location where rainfall, measured in the air by the radar, reaches the ground, according to the wind and to the speed motion of the storm.

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