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Thorndahl, Søren; Rasmussen, Michael R.

Published in:
UrbanRain09 : 8th International Workshop on Precipitation in Urban Areas : St. Moritz, Switzerland

Publication date:
2009

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Thorndahl, S., & Rasmussen, M. R. (2009). Challenges in X-band Weather Radar Data Calibration. In P. Molnar, P. Burlando, T. Einfalt, B. Schäppi, & M. Haas (Eds.), *UrbanRain09 : 8th International Workshop on Precipitation in Urban Areas : St. Moritz, Switzerland: Rainfall in the Urban Context : Forecasting, Risk and Climate Change : 10-13 December, 2009* (pp. 12-16). Eidgenössische Technische Hochschule Zürich, Laboratorium für Lebensmittel-Verfahrenstechnik.

CHALLENGES IN X-BAND WEATHER RADAR DATA CALIBRATION

by

S. Thorndahl(1) and M.R. Rasmussen(2)

(1) *Aalborg University, Department of Civil Engineeerring, Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark* (st@civil.aau.dk)
(2) *Aalborg University, Department of Civil Engineeerring, Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark* (mr@civil.aau.dk)

ABSTRACT

Application of weather radar data in urban hydrology is evolving and radar data is now applied for both modelling, analysis and real time control purposes. In these contexts, it is all-important that the radar data well calibrated and adjusted in order to obtain valid quantitative precipitation estimates. This paper compares two calibration procedures for a small marine X-band radar by comparing radar data with rain gauge data. Validation shows a very good consensus with regards to precipitation volumes, but more diverse results on peak rain intensities.

Keywords: weather radar, X-band, calibration, rain gauge, quantitative precipitation estimates.

1 INTRODUCTION

Most quantitative precipitation estimates for hydrological modelling purposes have in the past been measured with tipping bucket rain gauges, which operate in high temporal resolution, but unless multiple gauges are installed within a limited area with deficient spatial resolution. Spatio-temporally distributed quantitative precipitation estimates using weather radars has the benefit of high resolution in both space and time and have therefore become a rapidly expanding area of research within rural and urban hydrology concurrently with increase in radar data availability and more cost efficient radars (Einfalt et al. 2004).

One of these cost efficient radar types is the Local Area Weather radar developed by DHI, Denmark (Jensen and Overgaard 2002). This radar is produced on the basis of a marine X-band radar which makes it affordable compared to conventional weather radars. Quantitative precipitation measurements with conventional X-, C-, or S-band weather radars are classically based on theoretical relationship between radar power emission, reflectivity and rain intensity (e.g. Marshall and Palmer, 1948; Battan, 1973). The precipitation measurements with the Local Area Weather Radar, however, are based on a purely empirical relationship between radar reflectivity and rain intensity, due to limitations in the marine radar design, and therefore the traditional theory cannot be applied. So on order to obtain reliable rainfall measurements this type of radar has to be calibrated against rain gauges. This type of empirical calibration has previously been investigated by, e.g. Jensen (2002), Pedersen (2009), Rollenbeck and Bendix (2006), and Thorndahl and Rasmussen (2009) and is based on comparison of rain volumes recorded in rain gauges and radar respectively. In context of urban hydrology, it is essential to measure peak intensities with great precision, and therefore this paper will focus on the radar's ability to measure the peak intensities and how calibration should be performed in order to estimate both volumes and maximum values with satisfactory precision. This is investigated by comparing two quite different approaches of radar data calibration, firstly the more traditional volume approach in which rain gauge and radar data is accumulated for each rain event, and a linear regression is performed in order to find a linear relationship between the two, and secondly, an intensity based distribution fitting approach, in which the ratio between rain gauge and radar is calculated of each time step, so that a distribution of ratio can be derived. The latter method diverges from the methods presented by Jensen (2002), Pedersen (2009), and Rollenbeck and Bendix (2006) as these all use accumulated values. The analyses performed in this paper are completed with Aalborg Weather Radar as case (figure 1, table I), and the tipping bucket rain gauges presented in figure 1, The calibration is based on a period from July to December 2008, and validated on a period from May to August 2009 using the nine rain gauges presented in figure 1.

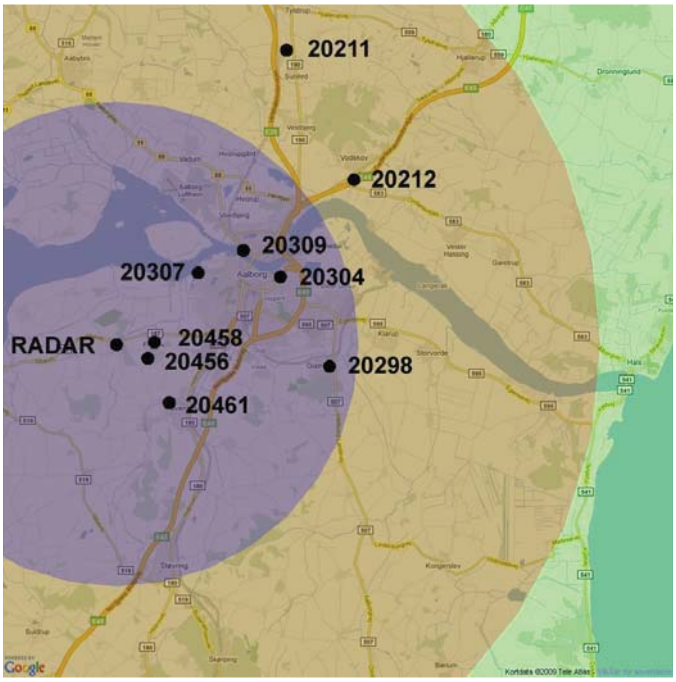

Figure 1 – Map of radar and rain gauges. The inner toned area covers 0-15 km from the radar and the outer toned area covers 15-30 km. Google Maps.

Table I - Specifications of the radar

Radar	Furuno 1525
Developer	DHI
Frequency	9.41 GHz
Wave length	3.2 cm (X-band)
Emmision power	25 kW
Temporal resolution	5 min
Spatial resolutions	500 x 500 m (range 60 km) 250 x 250 m (range 30 km) 100 x 100 m (range 15 km)
Angular resolution	0.95º azimuth
Vertical resolution	±10º
Data resolution	255 classes
Rotation	120 scans per 5 min

2 CALIBRATION METHODOLOGIES

The first calibration method is based on a linear regression between accumulated dimensionless radar output (*DRO*) and the accumulated rainfall depth (*d*) recorded in a rain gauge per rain event. A regression is performed for each rain gauge by extracting radar data from the 500x500 m radar pixel corresponding to the position of the rain gauge. As the radar has a relatively large vertical opening angle (±10º), the sampling volume increases as a function of the distance from the radar. In order to handle this phenomenon an exponential volume correction must be included in the calibration. This can be implemented directly in the radar software as presented by Pedersen et al. (2008) or, as it is done in this paper, by a posteriori fitting an exponential function to the rain gauge/radar ratio (β) as a function of the distance from the radar. The relationship between rain intensity (i), the radar output (*DRO*) and the distance from the radar (r) is then expressed by the two-parameter model:

$$i_{n,m} = c_1 \cdot \exp(c_2 \cdot r) \cdot DRO_{n,m} \tag{1}$$

c_1 and c_2 are parameters related to the exponential function.

As presented in the introduction the rain peak values are of great importance in urban hydrology, and these peak values are partly averaged out due to the accumulation over an event. Therefore, the second calibration method, henceforth named *the log-normal fit approach*, is based on smaller time steps compared to the regression approach. Here, the ratio between rain gauge and dimensionless radar output is calculated for each defined time step, in this case 5 minutes, and instead of one fitted value, a whole distribution of ratios can be derived. These are fitted to a log-normal distribution and for each location the two parameters ($\mu_{log\beta}$ and $\sigma_{log\beta}$) defining the log-normal distribution is derived. In order to include the distance from the radar the two parameters are fitted to the exponential function as done in the regression approach. The conversion from radar output to rain intensity is then defined as:

$$i_{n,m} = F^{-1}_{logN}(\mu_{log\beta}(r), \sigma_{log\beta}(r), P) \cdot DRO_{n,m} \tag{2}$$

This model includes five parameters in total as two parameters c_1 and c_2 are needed to define both $\mu_{log\beta}(r)$ and $\sigma_{log\beta}(r)$ as well as the quantile, P. This method is previously investigated by Godiksen and Poulsen (2009)

3 CALIBRATION RESULTS

The calibration is based on radar and rain gauge recordings from July to December 2008, counting 1207 individual events in nine rain gauges. Figure 2 presents the linear regression for each of the nine rain gauges. The derived regression line slopes are shown, in figure 4 as a function of the distance from the radar. Applying eq. 1 with the parameters from figure 4 it is possible to calibrate the radar in all points within the range of the radar, however Thorndahl and Rasmussen (2009) does not recommend that it is applied beyond 20 km from the radar origo. Figure 3 presents the derived log-normal distributions for each rain gauge location. It is obvious that the results of the two methods are similar, as the ratios derived from the regression approach are centered around the median values (the points with the highest probability) of figure 3. However, by using the log-normal fit approach, it is possible to estimate the uncertainties of the calibrations estimates at different distances from the radar.

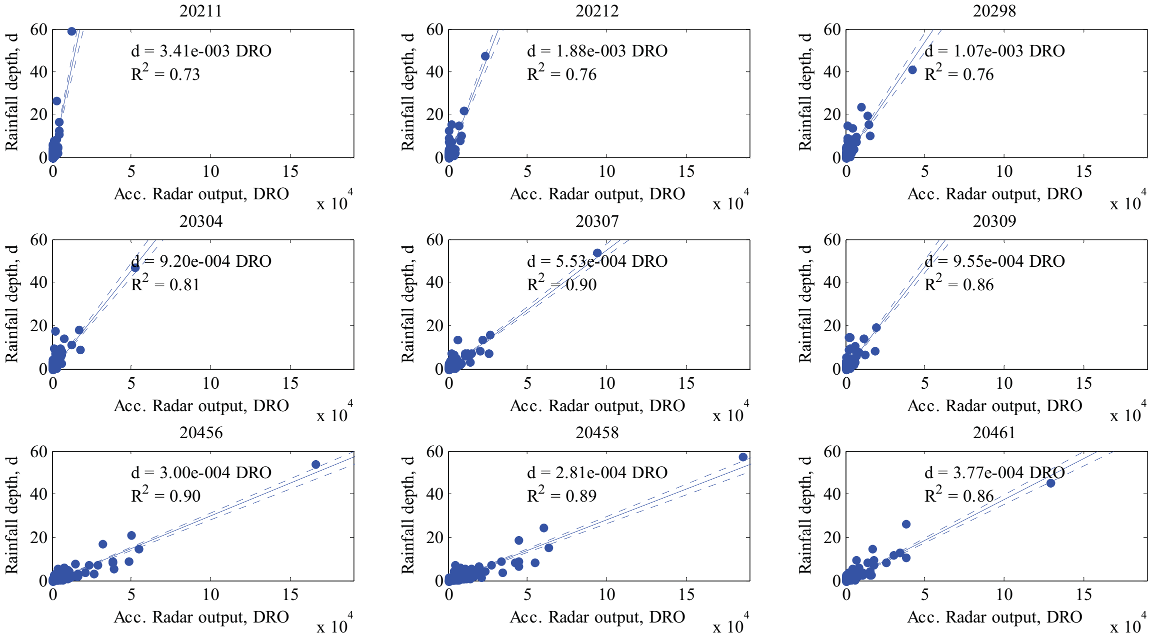

Figure 2 – Results of the linear regression calibration approach

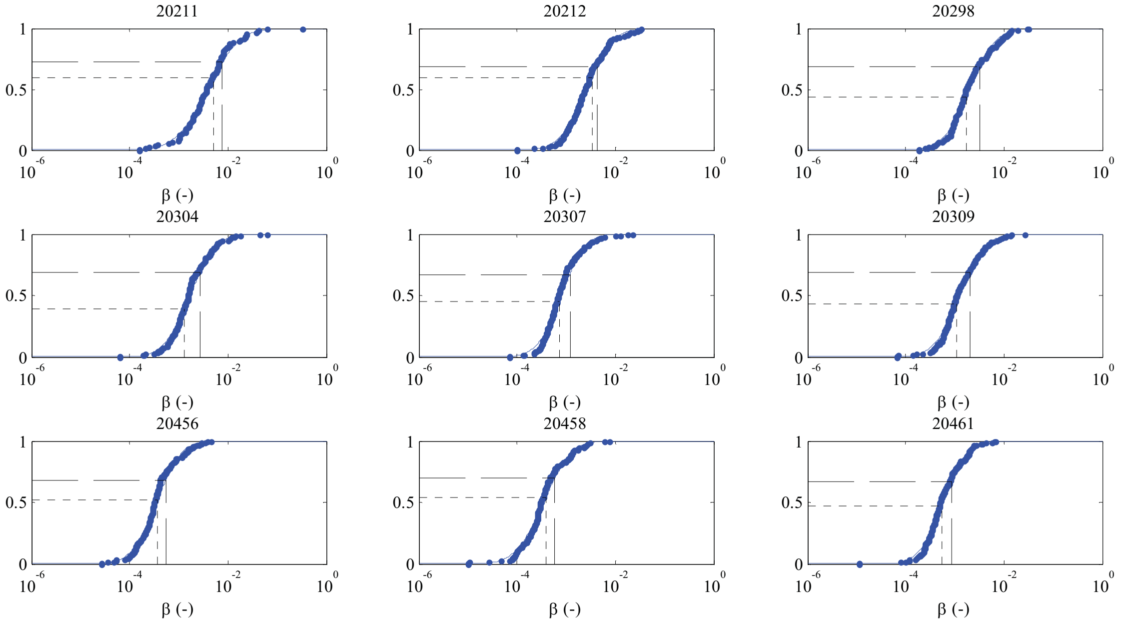

Figure 3 – Results of the log-normal fitting approach. Dotted lines indicates the β-values from the regression approach and dashed lines mark the mean values of the log-normal distributed data.

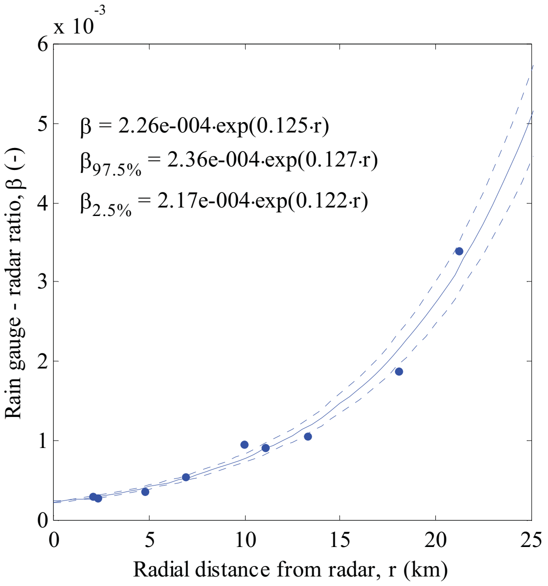

Figure 4 – Rain gauge/radar ratio as s function of the distance from the radar fitted to an exponential function.

Table II - Validation results.

Cali. method	Lin. Regression	Log-norm. fit (50 % quantile)	Log-norm. fit (75 % quantile)
Mean R^2	0.53	0.53	0.55
Std. dev. R^2	0.2	0.2	0.2
Mean Vol. error	-0.01	-0.01	-0.7
Std. dev. Vol. error	0.77	0.73	1.14
Mean peak error	1.87	1.78	0.76
Std. dev. peak error	2.72	2.56	1.44

3.1 Validation

The validation is based on recorded data from May to August 2009, counting 368 events in total. The validation is performed by calculation the correlation coefficient (R^2) between rain gauge and radar, the volume error and the peak error between rain gauge and radar for all 368 events. Table II shows mean values and standard deviations for each of the two calibration methods.

It is interesting that results are similar using the linear regression and the log-normal fit approach which is also seen in figure 4. The radar estimates the volumes compared to the rain gauges with less than 1 % error. However, examining the peak errors, it is obvious that the radar underestimates peak values quite significantly. Therefore, a validation using the 75 % quantile is performed. This obviously means a lack of mass balance, i.e. larger volume errors, but the peak error is reduced. Figure 5 shows a time series example of the two calibration methods.

It is however doubtful if is possible to always measure high peak intensities by a radar, as data is averaged over a large area in the atmosphere. In this case the radar covers an area of 250,000 m^2 (500 x 500 m) compared to the tipping bucket rain gauges which covers approx. 0.03 m^2. Nevertheless, it is possible to improve the fit, especially the peak values, between rain gauge and radar to some extent, by implementing a more dynamical calibration procedure, in which the calibration constants are changed continuously accordingly to the statistical distribution on figure 3. This procedure shortly described by Thorndahl et al. (2009). This dynamical calibration procedure requires real time rain gauge data, in order to calibrate the radar in real time. The concept is continuously to adjust the rain gauge/radar ratio according to recordings in a number of rain gauges and by the probability of a given ratio derived from the log-normal distributions.

4 DISCUSSION

Comparing the two presented calibration methods, it is obvious that they perform equally, i.e. the regression line slopes and the derived 50 % quantiles from the log-normal distribution are somewhat equal. This means that same results can be obtained regardless of the whether rain gauge/radar ratios are calculated by accumulation over an event or by individual time steps. The log-normal fit approach has the benefit that a whole distribution is derived, and therefore an indication of the variations in rain gauge/radar ratios is revealed. Even though it is possible to obtain minimal volume errors comparing radar and rain gauge, the radar is still quite far from a satisfactory prediction of the peak intensities. This has partly to do with spatial scale of the radar data, but introducing a dynamical calibration procedure, some of the peak errors might be reduced. The study of the statistics of the gauge/radar ratios also gives a unique possibility to study changes in model performances as a function of for examples distance, number of gauges and variations in meteorological parameters.

It can be evaluated on the spot if a given radar measurement is within normal operational range, or the measurement is at the extreme of the distribution. Depending on the application, different validity can therefore be attached to the observation.

Currently, results of the analyses of this paper is implemented to an on-line system, in which the radar data is used to forecast rain over five of the largest cities in Denmark. The forecasted spatio-temporal distributed rain is then used as input to a runoff model which simulates flow and/or water level in some selected key points of the drainage system. This system is presented in Thorndahl et al. 2009 and Rasmussen et al. 2008.

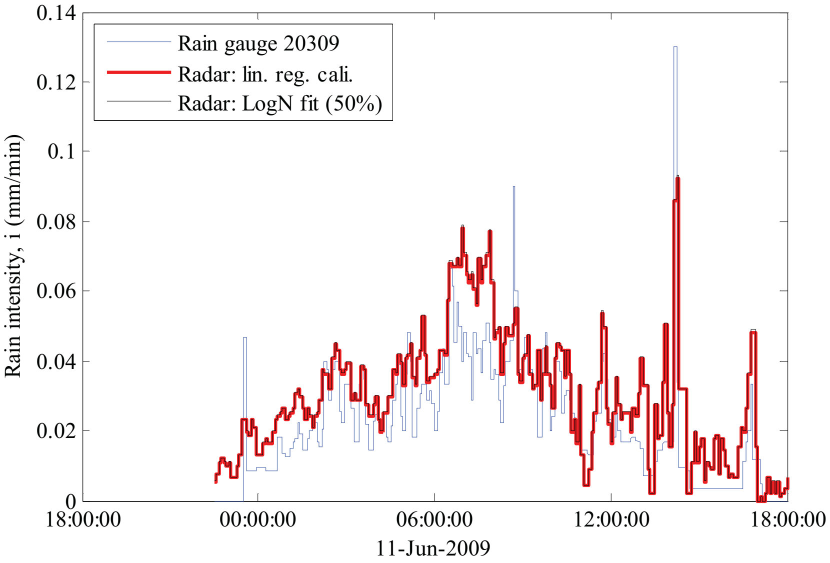

Figure 5 – Time series example of rain intensity measured by rain gauge and by radar using the two calibration approaches. R^2=0.68 for with regards to both methods.

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