Quantitative Precipitation Estimates Measured by C- and X-Band Radars

the potential for integration

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Quantitative precipitation estimates measured by C- and X-band radars – the potential for integration

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1. Introduction

Using weather radar for supplementing rain gauges in the field of urban drainage is now becoming more and more common. This is regarding almost all aspects in the field e.g. design, operation, real-time control and regulation of the sewer system e.g. (Einfalt et al. 2004, Borup 2008, Pedersen, Jensen & Madsen 2006).

Accounting for the spatial variability of the rainfall, combined with the large area coverage, are the major benefits of using weather radar. Especially when then application of the measurement is related to control and regulation of the sewer system or waste water treatment. The spatial variability is of course in general important, but in relation to actively controlling the system, the spatial extent and variability of the measurement is essential. The knowledge of the current state of the spatial distribution and temporal development of the precipitation is the basic requirement for short-term numerical precipitation forecast (now cast). Compared to control and regulation of the sewer system based only on in-sewer measurements and rain gauges, precipitation forecasts will significantly extend the possible lead-time and thereby the controlling possibilities. Several real-time control radar applications have been attempted within the last 25 years, where a project from Seine-Saint Denis, France belongs to the earliest (Bachoc et al., 1984).

When performing precipitation forecast based on radar, the range of the radar is fairly critical for the length of the lead-time, since it is only possible to forecast the precipitation detected by the radar (Rasmussen et al., 2010). Simultaneously a fairly detailed description of the precipitation is necessary to perform quantitative predictions of the precipitation. Even though the possible prediction period can vary conditioned by the actual weather situation (type of precipitation, wind velocity etc. (Einfalt et al., 2004)), a more accurate and longer range measurement is a better starting point for the rainfall prediction.

A typical trade-off for a longer range is a coarser spatial resolution (Einfalt et al., 2004), and radar measurements with both long range and high resolution are therefore not obtainable by a single radar. This aspect is basically the key motivation for this study. If this trade-off has to be made when using a single radar, combining the radars is an obvious solution. In this way a combined measurement with both the long range and high resolution is obtained.

Different types of weather radars ranging from massive long-range S- and C-band radars to small cost-efficient X-band radars are in operation to day and in Denmark it is quite common with dual coverage from both C- and X-band radars. The radars are operating with different configuration with regards to: antenna design, wavelength, scanning strategy etc, which results in different properties for the measurement. Specifications for the radars used for this paper are listed in table 1 and table 2.

Aau LAWR	X-band (Furono1525)
Frequency	9.41 GHz
Wave length	3.2 cm
Emmision power	25 kW
Temporal resolution	5 min
Spatial resolutions	500 x 500m (range 60km)
Angular resolution	0.95° azimuth
Vertical resolution	± 10°
Data resolution	255 classes
Rotation	24rpm
Scanning elevation	0°
(Thorndahl and Rasmussen, 2010)	

Table 1 Specifications: LAWR. The radar is based on a marine X-band radar

Sindal Radar	C-band
Frequency	5.625 GHz
Wave length	5.4 cm
Emmision power	250kW
Temporal resolution	10min
Spatial resolution	2000 x 2000m (range 240km)
Angular resolution	1°
Vertical resolution	± °0.5
Data resolution	255 classes
Rotation	3.3rpm
Scanning elevation	0.5°, 0.7°, 1.0°, 1.5°, 2.4°, 4.5°, 8.5°, 13.0°, 15.0
(Gill et al., 2006)	

Table 2 Specifications: Sindal Radar

Effects of these differences between radars are listed below:

- Temporal and spatial resolution
- Range
- Atmospheric attenuation
- Volumetric integration of the atmosphere
- Time-averaged estimates or discrete values in time

In the study a direct comparison of the C-band and X-band radar precipitation data is performed. Similar approach has been performed by (Pedersen et al., 2008) with the use of an S-band radar and LAWR (Local Area Weather Radar)(Jensen and Overgaard, 2002). The study was performed with the scope of evaluating the quality of the LAWR with the S-band

radar. The scope of this study however is in general to illuminate the possibility for integration of the two types of radars and to investigate the potential improvements by combining the two types of radars.

The comparison of the radar measurements are performed on the quantitative precipitation estimate measures by the two types of radars. This has been chosen because the radar systems are as described very different in configuration, thus a direct comparison on e.g. received reflectivity is not possible.

The comparison is performed on the levels listed below and is based on a LAWR Radar and a C-band radar - both calibrated on the basis of precipitation data from nine rain gauges.

- Accumulated volumes on event level
- Visual comparison
- Spatial correlation estimates

2. Methods

For the comparison an area of the northern part of Denmark is investigated. The area is covered by both a LAWR radar, a large C-band radar and is instrumented with nine rain gauges all of the tipping bucket type. The nine rain gauges applied for this study is a part of the Danish network of rain gauges (Madsen et al., 1998; Mikkeslen et al., 1998), manufactured by Rimco and operated by the Danish Meteorological Institute. The area of interest and the location of rain gauges and radars are illustrated on figure 1. The period for the comparison is an almost two month period from 1st of June to 27th of July 2009. Specification and total measured precipitation for the rain gauges is shown in table 3.

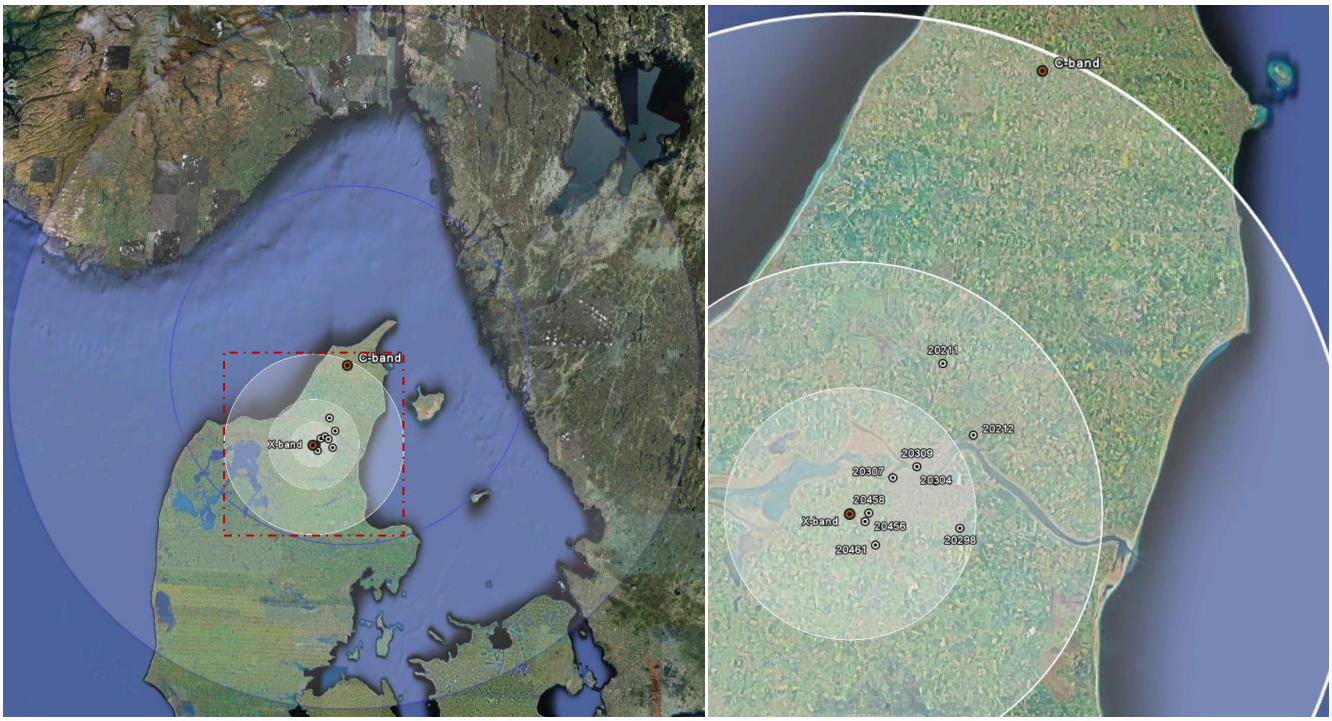

Fig. 1 Left: Situation of the radars with ranges of 15km, 30km and 60km for the X band radar and 120km and 240km ranges for the C-band radar. The red dashed square indicated the area of interest. Right: Close up of the rain gauges. (Google Earth)

Radar calibration

To be able to compare the measured quantitative precipitation estimates, it is necessary to convert the received reflectivity to rain intensities.

For conventional meteorological weather radars like the C-band radar, the relationship between received signal, drop size and the reflectivity is determined using the radar equation (Battan, 1973) and the Marshal-Palmer Z-R relation (Marchall and Palmer, 1948). By this relationship it is possible to calculate the rain intensities as a function of the reflectivity:

$$Z = A \cdot R^B$$

Where Z is the reflectivity, R is the rain intensity and A, B are the Marshall-Palmer constants. Experiences with Danish weather conditions has shown that values of A = 200 and B = 1.6 gives sensible results (Overgaard, 2004). In this particular study however, the Marshall-Palmer constants is calibrated on basis of the rain gauge measurements.

Gauge no.	Dist. from LAWR [km]	Dist. from C-band [km]	No. of recorded events	Total precipitation [mm]
20211	21.2	36.7	44	159.2
20212	18.0	43.6	44	146.4
20298	13.3	55.2	47	185.6
20304	11.1	50.5	38	171.8
20307	6.9	51.5	37	127.4
20309	9.9	49.3	40	131.6
20456	2.0	57.5	42	146.2
20458	2.4	56.4	42	133.4
20461	4.7	59.7	44	159.0

Table 3 Specifications and precipitation measured of the rain gauges

The LAWR radar is based on a marine X-band radar and has the advantages of being very cost-efficient compared to conventional weather radars. A disadvantage is that using the Marshal-Palmer conversion of reflectivity to rain intensities is not possible due to empirical processing of the radar reflectivity. Calibration against e.g. rain gauges is therefore necessary.

The radar output of the LAWR is a dimensionless radar output (DRO) and is conducted from radar video signal output (S) by two corrections factors γ_{VOL} and γ_{ATT} (Jensen, 2000; Thorndahl and Rasmussen, 2010):

$$DRO(r) = S(r) \cdot \gamma_{VOL}(r) \cdot \gamma_{ATT}(r)$$

The γ_{VOL} is volume correction and γ_{ATT} is attenuation correction. The volume correction is implemented due to the increasing sampling volume caused by the quite large opening angel of the radar ±10° and the attenuation correction is implemented, because the x-band electromagnetic waves are highly attenuated by the atmosphere (Jensen, 2000; Thorndahl and Rasmussen, 2010):

$$\gamma_{VOL}(r) = \frac{1}{a \cdot \exp(b \cdot r)}$$

r is the radial distance from the radar
a and b are constants, in this study *a* = 1 and *b* = -0.01

$$\gamma_{ATT}(r) = 1 + \frac{\alpha \cdot \sum_{r=0}^{R} S(r)}{C}$$

S is the radar output video signal (in mV)
C and α are constants, in this study C = 330 and α = 1

Ideally the dimensionless radar output (DRO) is an integer count value ranging from 0 to 255 linear proportional to the rain intensity and independent of the distance from the radar. In this particular study however it is has been chosen to do the volume correction within the post processing of the data instead of within the radar software. The calibration of the LAWR has therefore both the purpose of estimating the relation between DRO and rain intensities and the relationships' dependency of the radial distance. The relationship between the measured rainfall intensity *i* in gauge *g* and the radar DRO in pixel *n,m* is then expressed by:

$$i_g = \beta(r) \cdot DRO_{n,m} \quad \text{and} \quad \beta(r) = c_1 \cdot \exp\,(c_2 \cdot r)$$

β(r) is the linear relationship coefficient
r is the distance from the radar
c_1 and c_2 is the calibration constants in the exponential function

Due to the exponential nature of the volume correction function it is only applicable within the effective range of the radar, and cutoff range for the correction is chosen to 25km. The rain intensities within the range can therefore be calculated by:

For r < 25 km: $i_{n,m} = c_1 \cdot \exp\,(c_2 \cdot r) \cdot DRO_{n,m}$
For r > 25km: $i_{n,m} = \beta(25\ km) \cdot DRO_{n,m}$

The calibration of both radars is based on rain gauges data within the study area in the period from 1st of June to 27th of July 2009. Specification and total measured precipitation for the gauges is shown in table 3. The calibrations are performed as static event based calibrations using all the availed rain events. The result of the calibrated parameters for both radars is presented within figure 2 in result section.

Error of accumulated volumes on event level

To assess the overall performance of the radars, the relative error in accumulated volumes for each rainfall event is calculated. The precipitation measure of the rain gauge is considered as the true value:

$$Error = \frac{\sum_{event} i_r \cdot \Delta t_r - \sum_{event} i_g \cdot \Delta t_g}{\sum_{event} i_g \cdot \Delta t_g}$$

i_r and i_g are the rain intensities measured respectively by radar and rain gauge
Δt_r and Δt_g are the temporal resolution of respectively the radar and rain gauge measurement

Spatial correlation

To quantify the degree of agreement between the two radar precipitation estimates the two dimensional correlation coefficient R^2 is used:

$$R^2 = \left(\frac{\sum_{x=1}^{X} \sum_{y=1}^{Y} (C(x,y) - \bar{C}) \cdot (X(x,y) - \bar{X})}{\sqrt{\left(\sum_{x=1}^{X} \sum_{y=1}^{Y} (C(x,y) - \bar{C})\right)^2 \cdot \left(\sum_{x=1}^{X} \sum_{y=1}^{Y} (X(x,y) - \bar{X})\right)^2}} \right)^2$$

C is the C-band precipitation estimates
X is the LAWR precipitation estimates

Before it is possible to conduct this performance measure, the two sets of data has to be at both the same temporal and spatial resolution. To meet this requirement, the LAWR measurement has been averaged in space to a resolution of 2x2km fitting the C-band resolution. Furthermore only the square area of 40x40km with the LAWR in the center is investigated.

3. Results

Error of accumulated volumes on event level

In figure 2 the relative error of accumulated precipitation on event level are plotted for both of the radars. The errors are estimated based on the calibrated radar measurements and it shows that the majority of the events are estimated with a relative error within ±1 for both radars.

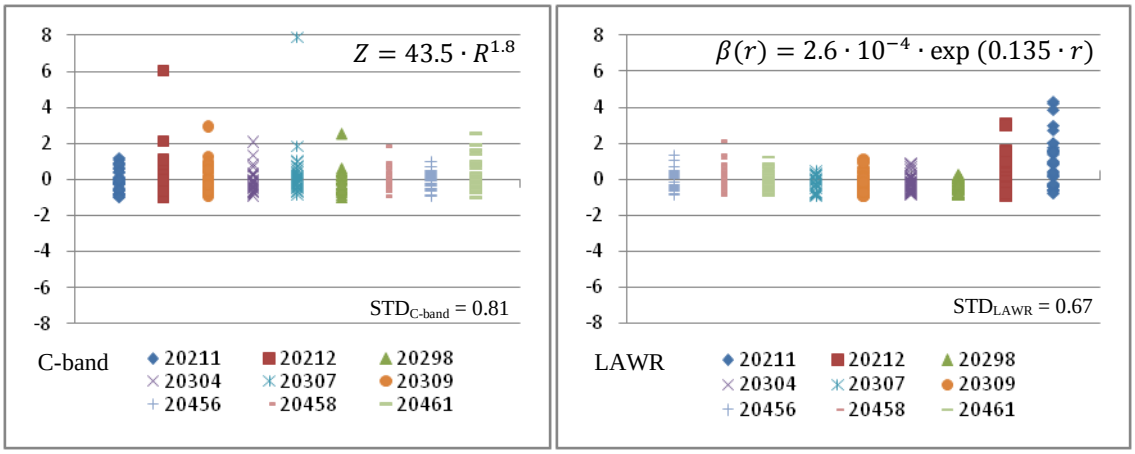

Fig. 2 The relative error between rain gauge estimates and radar estimates of accumulated precipitation on event level. For both radar the rain gauges is ranged after their radial distance from the radar with the nearest gauge furthest to the left.

The C-band radar has two events of significant over prediction, where the radar over predicts the rainfall with a factor of 6 and 7.8. For both events the gauge records a fairly small amount of precipitation (0.4mm and 1mm) and the errors could be caused by the large difference in spatial scale between gauge and radar measurement, meaning that the rain gauge measurement is not representing the precipitation for the 2x2km the radar is averaging over.

For the LAWR there is an obvious trend in the relative errors. It can be seen that the error of prediction the rainfall for the two rain gauges furthest away from the radar (Gauge no. 20211 and 20212) is larger. Due to the fact that the X-band waves are highly attenuated and the vertical opening angle is fairly high for this radar it is not surprising, that the quality of the LAWR measurement is decreasing with the range. The effective range of this type of radar is normally considered in the interval 15-20km , which also is shown in this case.

Considering the standard deviation of the relative error it suggests that the LAWR is performing slightly better than the C-band radar (STD$_{LAWR}$ = 0.67 STD$_{C\text{-band}}$ = 0.81), but if the two significant over predictions of the C-band radar is left out it is the other way around (STD$_{LAWR}$ = 0.67 STD$_{C\text{-band}}$ = 0.65). Based on this, the study shows that the radars is performing quite similar, and it is therefore difficult clearly to say which radar is performing the best overall rainfall estimates.

Visual comparison

As a part of the comparison a huge amount of corresponding spatial data from the two types of radars has been compared visually. Both cases of good and poor agreement between the two datasets can be found, but the overall perception of the visual inspection is that there exists a fairly good degree of similarity between radars.

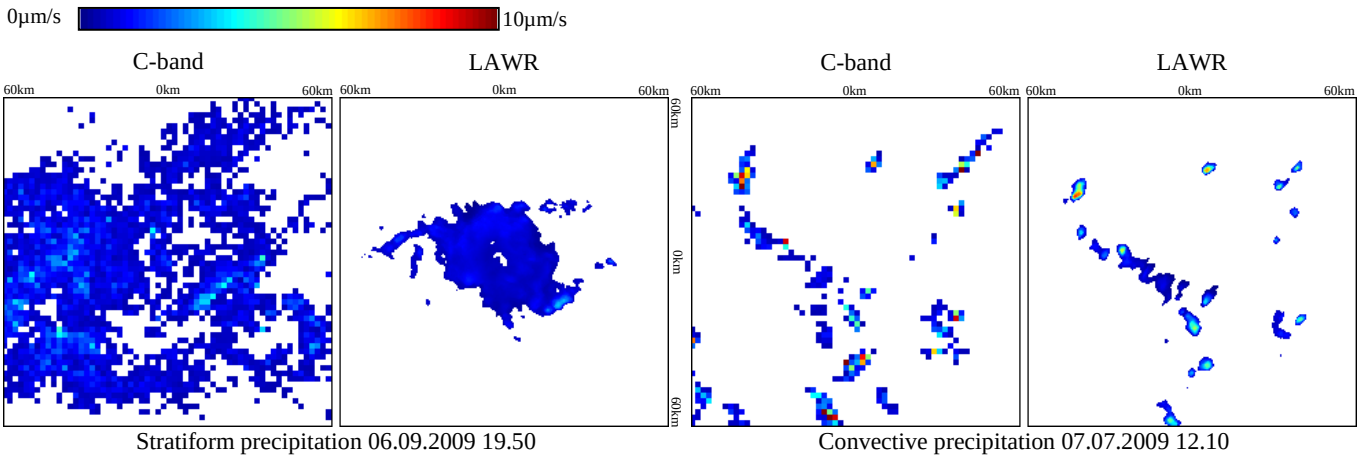

Fig. 3 Two sets of corresponding precipitation estimate from the C-band and LAWR. The set to the left is showing an event of stratiform precipitation with low rain intensities and large spatial extent. The set to the right is showing an event of convective precipitation with high rain intensities and small spatial extent of the rainfall.

Comparing the radar images visually it clearly reveals some strength and weaknesses for the two radar systems. As an example of this two corresponding radar images are illustrated in figure 3, where a stratiform and a convective rainfall event

are shown. Stratiform precipitation is typically associated with light rain and large spatial extend, generated from low clouds. As it can be seen the C-band radar detects a much wider spatial extend of the precipitation than the LAWR, and it clearly shows the disadvantage of the large vertical opening angle of the LAWR. Due to the large vertical opening angle and the low-laying rain, the upper part of the LAWR beam will break out of the precipitation quite close to the radar resulting in only partly filled sampling volumes and thereby poor observations further away.

In the case of convective rainfall, the vertical extent of the precipitation is much higher and partly filled sampling volumes are no issue for the LAWR radar. As shown in figure 3 (right) the LAWR radar is in this case capable of detecting rain at the full range even with high intensities. In this case of convective precipitation the disadvantage of low spatial resolution for the C-band radar becomes clear. Even though there is a fairly good visual agreement between the radar images, the result also shows that a 2x2km spatial resolution is too coarse to describe the spatial variations within the convective precipitation sufficient. Of course it is not possible to say, if the 500x500m resolution of the LAWR is completely sufficient, but it obviously shows a better description.

Spatial correlations between the radar measurements

The spatial correlation between the two radar measurements has been estimated for the rainfall period of the 6th of July 2009 in the time interval 18:00 to 20:10. The area for comparison is a 40km square with the LAWR located in the center and the LAWR data has been averaged in space to fit the resolution of the C-band radar. The result is shown in figure 4.

Visually the result shows a fairly degree of agreement between the images. Both estimation of shape and location of the precipitation are quite similar. Simultaneously it is also obviously that the images are not identical, which are also illustrated by the correlation coefficient calculated between the radar images. The correlation coefficient is ranging from R^2 = 0.17 to 0.77 with a mean for the time interval of R^2 = 0.40. Even though the correlation coefficient shows a level of agreement this agreement must be considered limited.

Some disagreement was expected especially when the differences of the working principle is taken into account. Just the difference in scanning strategy between the radars will result in different interpretation of the precipitation. When the LAWR is conducting the measurement by an average over time with a wide opening angle, the C-band radar is creating a 'snap shot' conducted from several scans in different elevations. But even though the effects for this aspect are not treated further within this study, it can be concluded that a fairly amount of similarities and agreement can be found, when the quantitative precipitation estimates of the two radars is evaluated and compared.

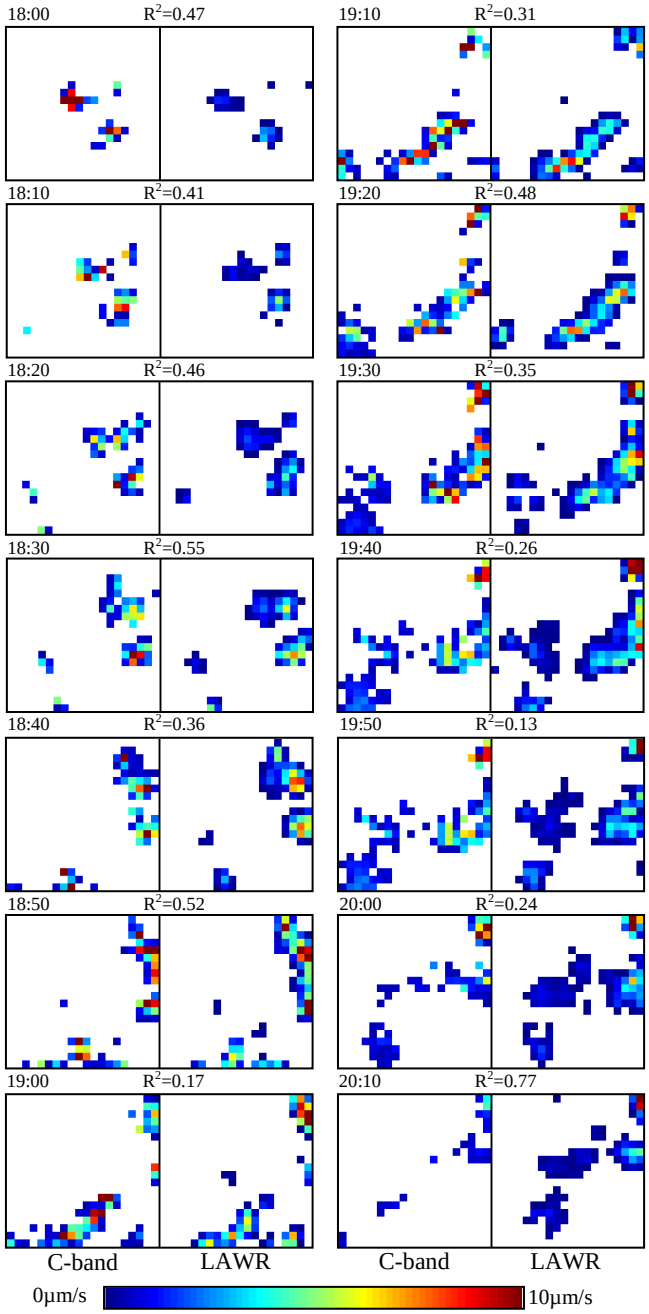

Fig. 4 Corresponding precipitation estimate for the C-band and LAWR form 06.07.2009. The LAWR is averaged in space to fit the C-band radar resolution of 2x2km. The area investigated is a 40x40km square, where the LAWR is located in the center.

4. Discussion

The purpose of this study was to gain more knowledge about the potential for improvements by combination and assimilation of the two investigated types of radars. As shown the two types of radars have both strengths and weaknesses associated with their working principle and thereby their measurements performance. It is difficult to conclude which radar is performing the best, both because the limitations of this study, but also because the performance has to be held in relation to the actual application of the data. For some purposes the range is of overall importance, while for others a high spatial resolution is crucial. The radars are however supplementing each other quite well and the results shows that a potential for combination of the two radar types is excising. In case for light and wide-spread rain the LAWR have a lot of difficulties in detecting the rainfall properly, while the C-band radar is more well-functioning under these conditions. The strengths of LAWR are in relation of the convection rainfall

with high vertical extend of the precipitation, and a distinction of type of precipitation will most properly be necessary if improvements based on combination of the radar measurements shall be performed.

Range and resolution are also areas with positive potential for improvements especially for the area beyond the effective range and within the total range of the LAWR radar. Even though the precipitation within this area is not well observed by the LAWR, it still can (in case for convective rainfall) contain a higher level of spatial variation of the precipitation than the C-band radar.

Finally it is general important to point out, that the illuminated differences is just as important as the similarities, because it is within the differences the possible improvements are hidden, while it is the similarities that makes the integration possible. That been said the challenges in combining measurements of so relatively different sources are considerable and further investigations and research are certainly needed.

5. Acknowledgment

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6. References

Bachoc, A., Delattre, J.M., Jacquet, G. & Frérot, A. 1984: Hierarchical monitoring of sewer systems. A case study: the Seine Saint Denis County, *Proc. 3rd International Conference on Urban Storm Drainage*.

Battan, L.J. 1973: Radar observation of the atmosphere, *University of Chicago press*.

Borup, M. 2008: Radar data for drainage calculations, Candidate thesis, Environment and Resources, Technical University of Denmark.

Einfalt, T., Arnbjerg-Nielsen, K., Golz, C., Jensen, N.E., Quirmbach, M., Vaes, G. & Vieux, B. 2004: Towards a roadmap for use of radar rainfall data in urban drainage, *Journal of Hydrology*, vol. 299, no. 3-4, pp. 186-202.

Gill, R.S., Overgaard, S. & Bøvith, T. 2006: The Danish weather radar network, *4th European conference on Radar in Meteorology and Hydrology, Barcelona 18th–22nd September*.

Jensen, N.E. 2000: Local Area Weather Radar Documentation v. 3.0 (2004), DHI, Institute for the water environment.

Jensen, N.E. & Overgaard, S. 2002: Performance of small X-band weather radar, *Western Pacific Geophysics meeting*, Wellington, New Zealand.

Jensen, N.E. 2002: X-Band local area weather radar - Preliminary calibration results, *Water Science and Technology vol 45-2*.

Madsen, H., Mikkelsen, P.S., Rosbjerg, D. & Harremoës, P. 1998: Estimation of regional intensity-duration-frequency curves for extreme precipitation, *Water Science and Technology*, vol. 37, no. 11, pp. 29-36.

Marshall, J.S. & Palmer, W.M. 1948: The Distribution of Raindrops with Size, *Journal of Atmospheric Sciences*, vol. 5, pp. 165-166.

Mikkelsen, P.S., Madsen, H., Arnbjerg-Nielsen, K., Jцrgensen, H.K., Rosbjerg, D. & Harremoës, P. 1998: A rationale for using local and regional point rainfall data for design and analysis of urban storm drainage systems, *Water Science and Technology*, vol. 37, no. 11, pp. 7-14.

Overgaard, S. 2004: The VRIS format of weather radar data, Danish Meteorological Institute.

Pedersen, L., Jensen, N.E. & Madsen, H. 2006, Application of local area weather radar (LAWR) in relation to hydrological modelling–identification of the pitfalls of using high resolution radar rainfall data, *Proceedings of the 4th European Conference on Radar in Meteorology and Hydrology, Barcelona*, pp. 414–417.

Pedersen, L., Zawadzki, I., Jensen, N.E. & Madsen, H. 2008: Assessment of QPE results from 4 kW X-band Local Area Weather Radar (LAWR) evaluated with S-band radar data, *ERAD 2008 - The fifth European conference on radar in meteorology and hydrology*.

Rasmussen, M.R., Thorndahl, S., Grum, M., Neve, S. & Poulsen, T.S. 2010: Vejrradarbaseret styring af spildevandsanlæg, By- og landskabsstyrelsen (in Danish).

Thorndahl, S., Rasmussen, M.R. 2010: Challenges in X-band weather radar data calibration, Submitted to Atmospheric Research 1th of July 2010.