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Regenerating high resolution data from a lower resolution weather radar

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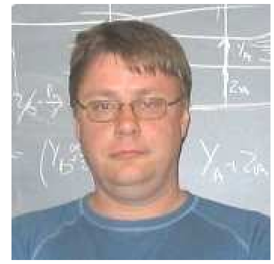

Michael R. Rasmussen

1. Introduction

Short range weather radars based on marine radars (Jensen and Overgaard, 2002) are very useful for real-time control of sewer systems. An example of real time application is for example weather radar based control of wastewater systems (Thorndahl et al, 2009). Because the urban hydrological catchments are very close to each other and because the runoff can end up at different destinations, it is important to measure precipitation with a high degree of spatial resolution. Using cost effective – but short range radars makes it possible to have cooperating radars which can cover the same areas from different positions. The many radars can eliminate some of the drawbacks with high ground clutter and beam blockage which can contaminate the signal.

The drawback of using the smallest marine radar types is that they have a horizontal beam width of between 4 and 5 degrees. For very short ranges (until approx 5 kilometers), the resolution is still acceptable for urban drainage applications. However, beyond this distance, the resolution deteriorates too much. The challenge is then: How to extend the range without having to change the system completely? A logical approach would be to change the antenna to for example a parabolic antenna with a narrower beam width. Although possible, this solution would require considerable modifications and make the principle of low cost and simplicity less true. But then – what to do?

2. The problem

The first step in solving the problem is to recognize that the measuring principle in all radars is a compromise between distance and resolution. The geometry of microwave propagation implies that the further away from the source, the wider the measuring area. For urban drainage purpose, the spatial resolution of the precipitation should ideally be as uniform as possible, so that the position of the radar in relation to the catchment does not influence the results.

Defining the ratio between angular and radial distances in a PPI as:

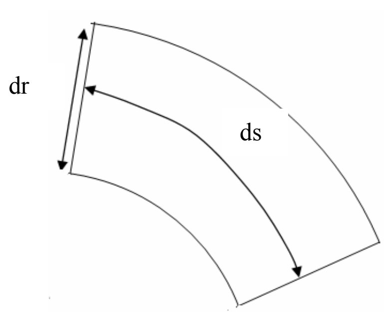

FIG. 1. Definition of the spatial resolution ratio.

The spatial resolution ratio (SRR) is simply defined as:

$$a = \frac{ds}{dr} \tag{1}$$

where *a* is the spatial resolution ratio, *ds* is the angular distance and *dr* is the radial resolution.

It is of course understood that this type of representation is a severe simplification of the actual measurement. The *dr* is directly related to the sampling frequency of the AD converter used. The angular distance, *ds*, is in this case a relationship with the distance from the radar.

$$ds = \frac{2\pi r}{n} \tag{2}$$

where r is the distance to the radar and n is the number unique directions for the radar.

Combining equation (1) and (2) yield for a small marine radar with a 5° antenna and a radial resolution of 100 meters opening yields a SRR of 1.0 already at a distance of 1.2 km. At a distance of 15 km the SRR is 13.1 which imply a much distorted resolution. For a 1° antenna, the SSR at the same 15 km would approximately 2.6.

The discussion above assumes that we can simplify the gain of the antenna as a top hat profile and that the radar moves the antenna angular resolution. Of course, in reality, the antenna moves continuously and the antenna beam pattern is dominated by a main lope and several side lopes. The process is basically a convolution process, where the beam pattern is multiplied with the object pattern (i.e. precipitation or ground objects). The convolution and deconvolution process can be achieved by applying FFT (Dombai,1995) or by using simple numerical solution of the convolution process (as done here).

The method is well known within digital signal processing and image processing. For example to enhance astronomical images acquired by either radio or optical instruments (Cornwell, 2008). The key is to estimate the point spread function (PSF) which describes how the i.e. light is distorted in the optics. For radar application the PSF is the antenna gain pattern.

To summarize, the problem is twofold: 1) At long ranges, the beam width is very wide compared to what is desirable and 2) The beam pattern of the antenna convolutes the signal. It is therefore logical to try and utilize that the antenna moves at smaller increments than the beam width and to use the knowledge on the beam pattern to deconvolute the signal to a higher spatial resolution.

3. Material and Methods

In order to investigate this problem, a smaller marine X-band radar is used. The data of the Furuno 1715 is listed in table 1. Besides being a low power X-band radar, the radar has a relative large angular resolution of 5.2°.This is fully acceptable for its original purpose of marine navigation, but as stated above very coarse for urban drainage applications beyond 5 km.

Table 1. Radar specifications (X-band).

X-band (Furuno1715)	
Frequency	9.41 GHz
Wave length	3.2 cm
Emission power	2.2 kW
Temporal resolution	1 min
Radial resolution	100 meter
Angular resolution	5.2 ° azimuth
Vertical resolution	± 10°
Data resolution	255 classes
Rotation	24rpm
Scanning elevation	0°

The antenna design is a patched array antenna with an asymmetrical resolution. The vertical resolution is ± 10°. For simplicity it is assumed the large vertical opening integrates vertical variations in the lower atmosphere. Thereby the measurements are truly reduced to a 2D planar dataset

The video signal from the radar is sampled with a Picolog 3602 digital oscilloscope with a sampling frequency of 100 Mhz. As a feature of this radar, the antenna is rotated by a step motor via a belt drive. This makes it possible to take full control of the antenna speed and direction.

FIG. 2. Furuno 1715 with patched array antenna.

In standard LAWR radars, the data are sampled on the fly, where 1-2 shots in each direction is possible as the antenna moves around. The same direction (scan line) is sampled after one revolution (2.5 seconds) until 1 or 5 minute averages can be produced.

In the case of the Furuno 1715 - by manipulating the step motor it is possible to move the antenna with 1.5^{o} increments. The sampling in one direction can therefore continue until sufficient number of datasets is recorded. One revolution still take around 1 minute, however, the dataset from each direction are more temporal correlated as the scan lines are recorded with around 100 Hz. The measurement typically consists of 20 scan lines with 4000 samples in each direction. The samples are filtered into bins with a radial resolution of 100 meter. The scan lines can subsequent be treated as described in (Pedersen et al 2010).

The antenna beam pattern is not fully known, however, the beam width (-3dB) is 5.2^{o}. By assuming that the side lopes for this experiment is small, the main lope is assumed to be Gaussian (Probert-Jones, 1962):

$$g(\theta) = g_0 e^{\left(-\frac{2\theta^2}{\theta_0^2}\right)} \quad (3)$$

where $g(\theta)$ is the linear gain at the angle θ, θ_0 is the beam width of the main lope and g_0 is the maximum gain.

Equation (3) is resample in 1.5^{o} distances from -7.5^{o} to 7.5^{o} to generate a discrete version of the PSF function. These 11 factors are used to convolute and deconvolute the signal.

In practical terms, as we assume that each measurement at a fixed distance and a fixed direction is a result of convolution of reflectivity from neighboring directions (in this case from -7.5^{o} to 7.5^{o}), we can simply establish one equation with 11 unconvoluted reflectivities. Moving the radar 1.5^{o} in one direction makes it possible to establish a new equation with 11 unknowns. However, the 10 unknowns are overlapping with the previous measurement. Continuing this process all the way around makes it possible to establish n equations with n unknown, which is easily solved with .i.e. Gauss-Seidel.

This is repeated at increasing radial distances from the radar (in this case in increments of 100 meter)

It is clear for all kind of discrete deconvolution methods that nothing is for free. Only using a discrete version of the antenna gain pattern will induce higher frequency noise into the results. It is therefore expected that the method will introduce negative values of precipitation using the LAWR methodology.

4. Results

4.1 Artificial data

The major challenge when trying to improve weather radar data resolution is that it is often very difficult to evaluate the quality of the results. The next best thing is to experiment with artificial data, because we decide ourselves what the "truth" is. In this work, the precipitation is modeled as 2D Gaussian distributions.

$$f(x,y) = Ae^{-\left(\frac{(x-x_0)^2}{2\sigma_x^2}+\frac{(y-y_0)^2}{2\sigma_y^2}\right)} \tag{4}$$

where A is the Amplitude, x_0 and y_0 is the center position of the distribution.

Equation (4) is for convenience formulated in Cartesian coordinates, but could just as well be in polar coordinates, as it is later converted into this coordinate system.

The process of generating artificial data is as follows:

1. Establish a number of artificial rain cells with equation (4).
2. Transform the data into a polar grid with 1.5° and 100 meter resolution.
3. Convolute the data with equation (3).
4. Remap result to Cartesian image.

In this example a quarter of a radar image is examined. The radar is placed at the upper left corner. The extent of the area is 20 km x 20 km.

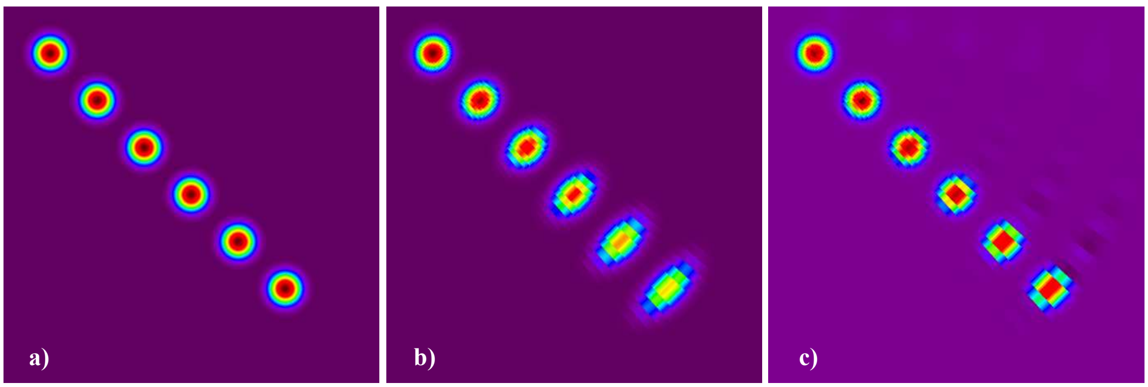

FIG. 3. a) Artificial rain cells, b) Transformed and convoluted data and c) enhanced data.

It can be seen from figure 3 that the further from the radar, the rain cells are, the more blurred and undefined they become. Also, the gain pattern of the 5.2 ° antenna smears the outer rain cells more that the closer cells.
When the data are deconvoluted in figure 3 c) the spatial extent of the rain cells are reestablished. It is also clear from figure 3c that the angular resolution only to a certain extent is enhanced.
In a more complex example, different rain cells are place randomly around the area and have different extent and spread. Some of the cells are overlapping each other creating more complex images, which are found in real weather radar da

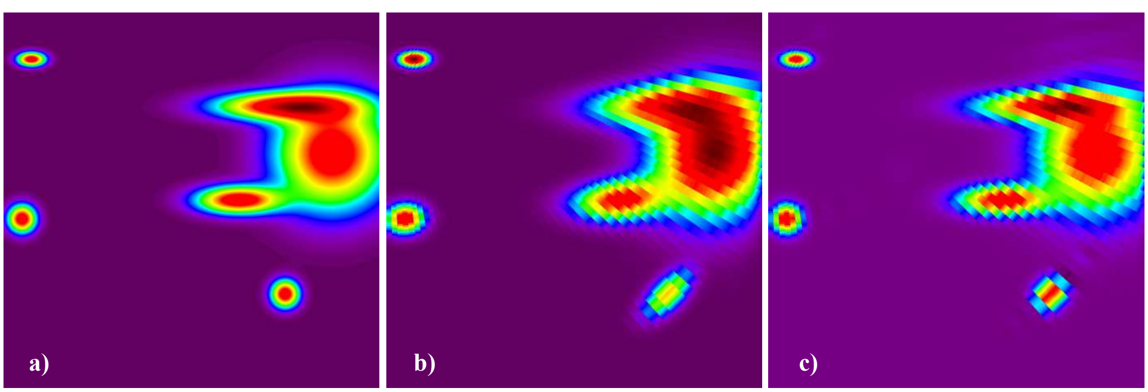

FIG. 4. a) Artificial rain cells, b) Transformed and convoluted data and c) enhanced data

Looking at the right side of the image a larger area with a high intensity cell inside is blurred after the transformation and the area now is a more wide spread area with higher intensity. After the enhancement the cell with high intensity is now visible again and has the same extent as the original data. This would in an urban drainage application create a large difference in the subsequent runoff.

The enhance data could get closer to the original data if it was possible to measure in smaller step than 1.5º. However, in this example the purpose was to emulate the Furuno 1715 marine radar. It is also clear from figure 3 and 4 that the deconvolution with a discrete PSF generates higher frequency noise in the image and thereby creating negative values.

4.2 Field experiment with static target

In order to test the method a field experiment is performed. The radar is targeted at Hals Bare Lighthouse in Hals, Northern Denmark. The lighthouse is located 10 km from the coast and is made in granite.

FIG. 5. Hals Bare Lighthouse – the experimental radar.

The lighthouse is at that distance regarded as a single point. The radar is then slowly rotated 1.5º. After each step 20 scan lines are sampled in that direction. The 20 scan lines are averaged into one scan line.

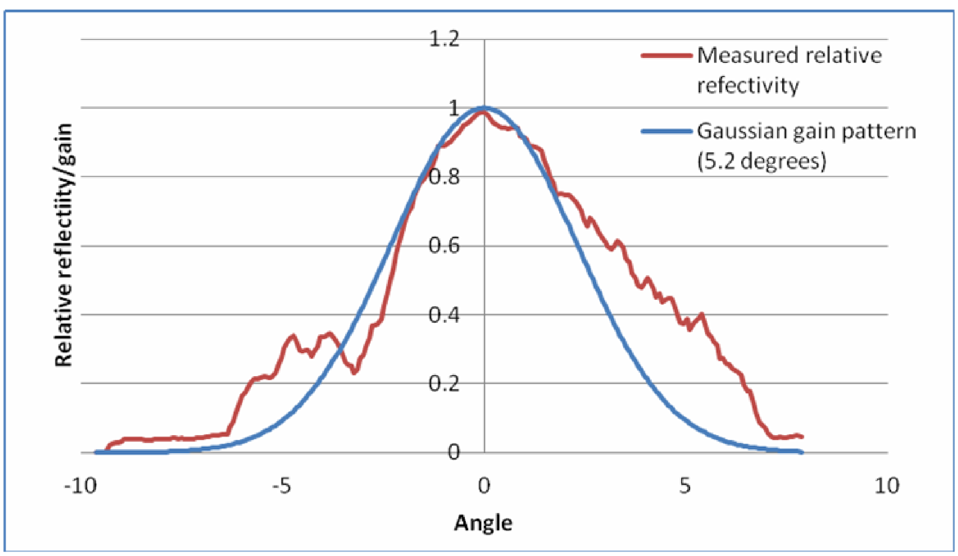

FIG. 6. Comparison between reflectivity from the lighthouse and a Gaussian gain pattern.

The relative reflectivity is in figure 5 plotted against the theoretical gain pattern. As can be seen, the measured reflectivity is comparable to what is expected from this antenna.

It is now possible to reconstruct the deconvoluted signal from the measurement.

5. Conclusion

The results illustrates that it is possible to regain some of the lost resolution from a small weather radar with coarse angular resolution. By measuring with significant smaller angular steps than the beam width and by deconvoluting the data, a more detailed image appears. Using this principle on artificial data, it is possible to compare the enhanced data with the original data for comparison.
Using a fast - but crude - deconvolution process requires care with subsequent processing of the data as negative precipitation can appear.

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