

## Progress Towards Developing a Radar Calibration Method for Improved Rainfall Estimation

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### *Abstract*

It is well recognized that there exists a need for accurate prediction of precipitation, whether it is for improvement of flood warning systems, water system management, or groundwater recharge assessment (Krajewski and Smith, 2002). Weather radar has enabled us to improve our quantitative observations of precipitation in the field of radar hydrology. However, radar-based estimates of rainfall accumulation and/or rate are subject to numerous uncertainties. Some errors may arise due to the inherent complexity of the mechanical and electronic system of detection while others may be due to the complexity of the terrain. As a result, the relation between measured radar reflectivity and surface rainfall is highly complex and can be influenced by many factors (Austin, 1987). Even though it has been the subject of many studies, no satisfactory method has been developed to date for accurately estimating rainfall when high spatial and temporal resolution is required (Anagnostou and Krajewski, 1997).

We propose to develop an approach to calibrate radar by applying a mathematical method originally proposed by Carasso *et al.* (1978) for image processing. The method of the Marching-Jury Backward Beam Equation (Atmadja and Bagtzoglou, 2001a; Bagtzoglou and Atmadja, 2003) is studied and then coupled to discrete Fourier image processing techniques to solve a two-dimensional (2D) problem with homogeneous diffusion coefficient backwards. The difficulties associated with this ill posed, backwards diffusion problem are well recognized (Atmadja and Bagtzoglou,

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2001b). We, therefore, enhance the method by integrating an optimization scheme that takes as input parameters the stabilization parameter and the coefficient of diffusion. The objective function is set as a weighted sum of different mass and peak errors that can be calculated based on gauge data available at the watershed under study.

The algorithm is then tested on the Mansfield Hollow (MH) Watershed in Connecticut, where both radar and rain gauge data are available during the same period of time. The 2D digital radar image data are considered degraded by an *a priori* unknown diffusion process and we attempt to perform restoration following an optimization approach that uses the rain gauge data as conditioning points in space-time. These point measurements not only provide us with an extra set of constraints that facilitate the optimization process but also allow us to assess our method's accuracy by comparing the radar-based rainfall estimates with those obtained from rain gauge networks (Collier, 1986a; b). The result of the optimization process produces optimum parameters that are needed for the conversion of the radar measured reflectivity data into radar predicted rainfall intensities. We expect our method to provide us with a better correlation between radar and rain gauge data as well as a tool to automatically adjust radar rainfall estimates.

### ***Introduction***

In order to obtain accurate radar data that will be useful for rainfall estimation and prediction, it is evident that we need to find a method that will allow us to systematically convert reflectivity measurements,  $Z$ , into rainfall data,  $R$ . One reason this is a very challenging problem is that radar and rain gauge measurements are acquired at completely different spatial and temporal scales. Rain gauges provide continuous measurements at discrete points in space, whereas radar provides spatial snapshots obtained at discrete points in time with resolutions in space in the order of  $4\text{km} \times 4\text{km}$  for NEXRAD, or  $150\text{m} \times 150\text{m}$  for typical X-band polarimetric radar. Keeping that in mind, the question is then what method should be used to convert reflectivity measurement into rainfall data?

Hydrologists often adjust radar data by comparing it to rain gauge data. The basic idea behind our work is that radar data can be adjusted in order to accurately reflect the point measurements of rain gauges and yet retain the spatial variability in rainfall intensities as measured by radar at large spatial scales. It is then not surprising that most radar calibration methods are based on ground validation using information from rain gauges. Moreover, it is not surprising to find dozens of different ways of calibrating radar in the literature, as the issue of radar calibration has been the focus of many studies. This issue is actually still the center of attention for many scientists because the following critical question has not yet been answered: what is the best "combination method" that allows one to make the best use of those two types of measurements in order to obtain accurate spatial rainfall estimation?

The literature shows that as soon as radar was considered useful as a tool for quantitative measurements, it became almost customary to compare radar data with rain gauge data. As early as in the mid-seventies, Zawadzki (1975) suggested a method to determine the optimum  $Z-R$  relationship that would minimize the random errors and bias, thereby improving hydrological measurements. His approach consists of determining a  $Z-R$  relationship by spatially smoothing the data and finding the optimum time over which the data could be integrated. Later, Austin (1987) proposed a different approach in that she attempted to understand the physical factors influencing the discrepancies observed between radar and rain gauge measurements. Some of the factors she looked at were the raindrop size distribution, the diminution of reflectivity due to downdraft associated with heavy rain in convective cells, or the enhancement of the signal because of the presence of hail. She clearly stated the problem of sampling, and discussed the fact that there is not necessarily a need to compensate the data for the factors she is describing if sufficient data are accumulated over time. However, if one sought accurate spatial rainfall distribution on a storm-to-storm basis, then she suggested correcting the radar data depending on what type of storm is occurring. Recently, Seo (1998) has developed a procedure that showed promise of improving the accuracy of estimating rainfall. In this framework, one accounts not only for within storm variability through bias correction and multi-sensor estimation, but also for variability due to the fractional coverage of rain. In other words, Seo tries to account for the fact that there is some probability of successful detection associated with radar measurements and that some areas under the radar coverage may in fact receive no rain at all. Even though this method showed very encouraging results Seo (1998) recognized that there is still a need to not only improve rainfall estimation procedures, but also to implement algorithms that would enable real-time estimation of rainfall, which is particularly important in the context of flash-flood forecasting.

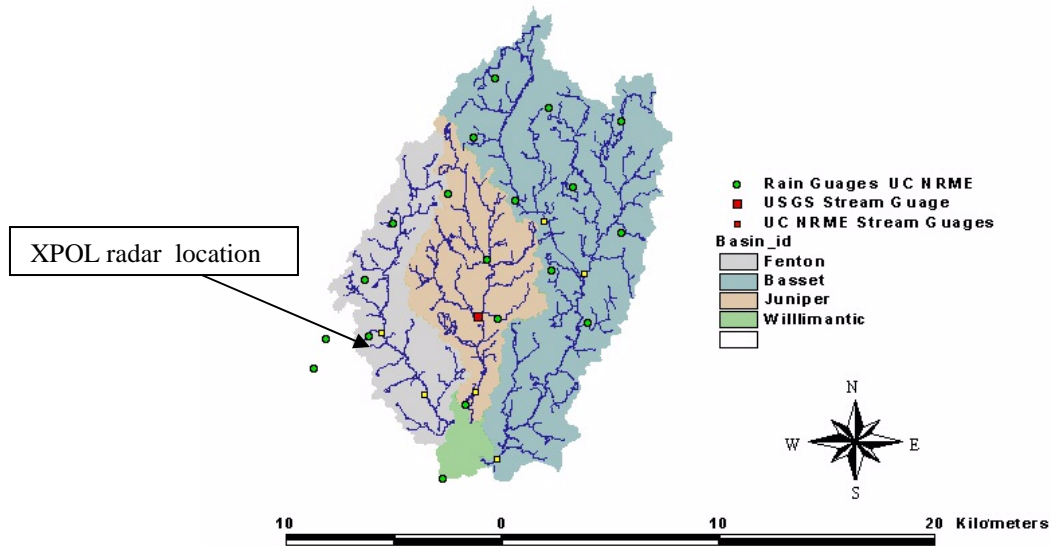
Most schemes that were developed to routinely adjust radar measurements are still in use today. For example, the Meteorological Office in London (NIMROD radar Network) calculates an adjustment factor on a weekly basis based on available gauge data, provided of course that sufficient data have been accumulated. The United States National Weather Service (NEXRAD radar) employs an adjustment factor on an hourly basis using a Kalman Filter approach. Gibson (2000) clearly recognized that even though those schemes are operational, there is definitely substantial room for improvement.

### *Description of the Study Site*

The Mansfield Hollow Watershed is a 427km<sup>2</sup> basin located in northeastern Connecticut with its western border adjoining the University of Connecticut Storrs Campus. This watershed offers highly vegetated and forested land cover in a thinly settled environment of both coniferous and herbaceous tree stands. Watershed soils are glacial till deposits that can be described as young, sandy loams. The runoff generation mechanism is typically saturation excess that can only be activated by

relatively heavy rain in moist conditions. A 2D plan view of the watershed is provided in Figure 1. In general, the hill slopes in the basin are rather gentle.

Within the study area, a mobile X-band dual polarization radar (referred to as XPOL radar) provided measurements of reflectivity. The XPOL operates at a wavelength of 2.98cm and a 50kW peak transmitting power, sending out and receiving electromagnetic pulses on two polarization planes. In this study, the radar operated at a 150m-pulse length resolution and an approximate 0.95-degree beam width. Horizontal backscatter reflectivity is our observable of interest. These measurements are available at a high resolution (150m × 150m) and covering an area of 3,600km<sup>2</sup>. Spatial maps of rainfall are, therefore, derived from XPOL high-resolution radar observations. However, the data obtained at a resolution of 150m × 150m were oftentimes degraded to a canonical grid of either 300m × 300m or 1200m × 1200m for ease in data management purposes, depending on the specific problem at hand. Within the area covered by the XPOL radar there exists a network of 16 rain gauges that provides rainfall data every 15 minutes. Since the XPOL radar is capable of providing reflectivity fields every 5 minutes, averaging 3 subsequent 5-minute snapshots is needed to produce information compatible with the 15-minute based rain gauge data.



**Figure 1. Map of the Mansfield Hollow Watershed, with rain gauge and XPOL radar locations.**

### ***The Bagtzoglou-Baun Method***

In this work, we propose a completely different and new approach for radar calibration. Our method, named after the two senior authors of this paper, is based on image processing techniques as originally proposed by Carasso *et al.* (1978), and further enhanced by the implementation of an optimization scheme. The adjustment

or calibration of the radar is still performed based on comparison with data obtained from the rain gauges. However, in this scheme, the 2D maps of radar reflectivity are considered degraded by an artificial and *a priori* unknown diffusion process. The idea is to restore those images following our optimization approach and using rain gauge data as the means for space point conditioning. The fine-tuning is possible thanks to two input parameters, namely the time- and possibly space-dependent coefficient of diffusion  $K$  and the inversion stabilization factor  $s$  that directly affect the restoration process. Those parameters are considered optimized once all radar data corresponding to the gauge locations have values as close as possible to the observed rain gauge data.

Obviously, for this method to be able to compare the radar data with the rain gauge data at the 16 locations of interest, we need to convert the radar data into rainfall. Several reflectivity-to-rainfall ( $Z$ - $R$ ) relationships have been developed and tested both recently and historically (Brandes *et al.*, 2002; Marshall and Palmer, 1948). The general formulations agreed upon suggest that rainfall can be approximated as a function of reflectivity via a power-law relationship:

$$R = \alpha (Zh)^\beta$$

Typically,  $Zh$  is expressed in  $\text{mm}^6/\text{m}^3$  and  $R$  is expressed in  $\text{mm/hr}$ .

Horizontal polarization reflectivity fields can be converted to rainfall fields provided the parameters of this functional form are resolved. To accomplish this, disdrometer data from the NASA Wallops field facility were selected. This facility offers simultaneous point rainfall and drop size distribution measurements. Radar scattering calculations were applied to the drop size distribution parameters to estimate theoretical radar observations (Ishimari, 1991). Therefore, a continuous set of rainfall ( $R$ ) and corresponding simulated reflectivity ( $Zh$ ) data were fitted to the above functional relationship resolving the  $\alpha$  and  $\beta$  parameters via a generalized inverse of the following linearized equation:

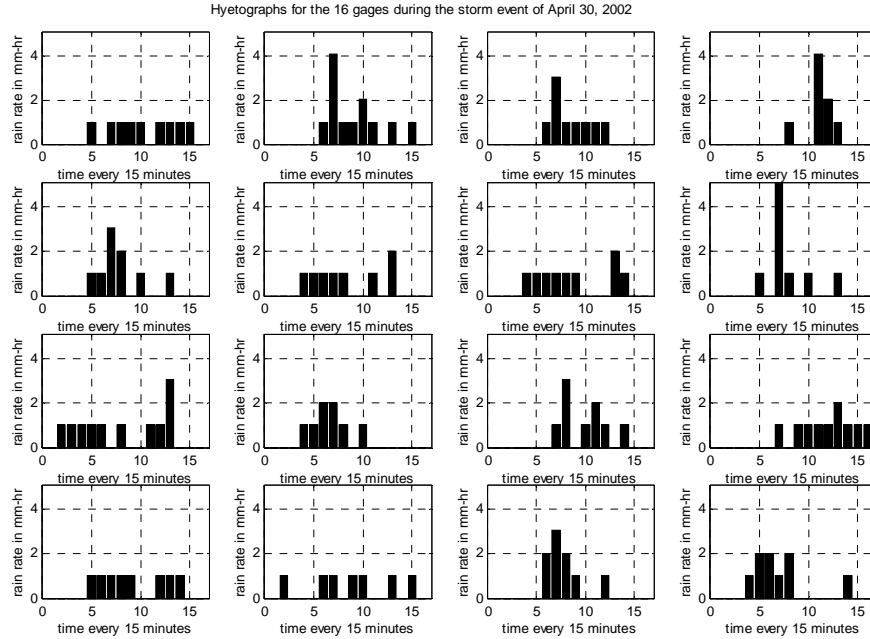
$$\ln(R) = \ln(\alpha) + \beta \ln(Zh)$$

The initial values that we use to run our programs are:  $\alpha = 0.038$  and  $\beta = 0.6072$ .

The starting point of this algorithm is a  $Z$ - $R$  plot of all the radar snapshots and the calculation of errors. After the data are processed through image restoration, new reflectivity maps are generated thereby allowing us to plot a new  $Z$ - $R$  curve, which will be more representative of the watershed than the initial one. This optimization process will hopefully achieve two tasks: 1) the correction of the entire map of measured reflectivity based on rain gauge data, and 2) the derivation of the optimum parameters needed for the conversion of the radar measured reflectivity data into radar predicted rainfall intensities.

## Storm Data

In this paper, we concentrate on the storm event of April 30, 2002, which lasted approximately 4 hours. Figure 2 depicts the 16 hyetographs showing the rainfall rate data that were recorded during that storm at the gauge network. From the XPOL radar, we were able to retrieve the corresponding radar data for 3 consecutive times that appear to have the most rain activity. These consecutive times, namely 22:50, 22:55, and 23:00 have been averaged over a 15-minute interval in order to produce data that are compatible with the 15 minute based rain gauge information.



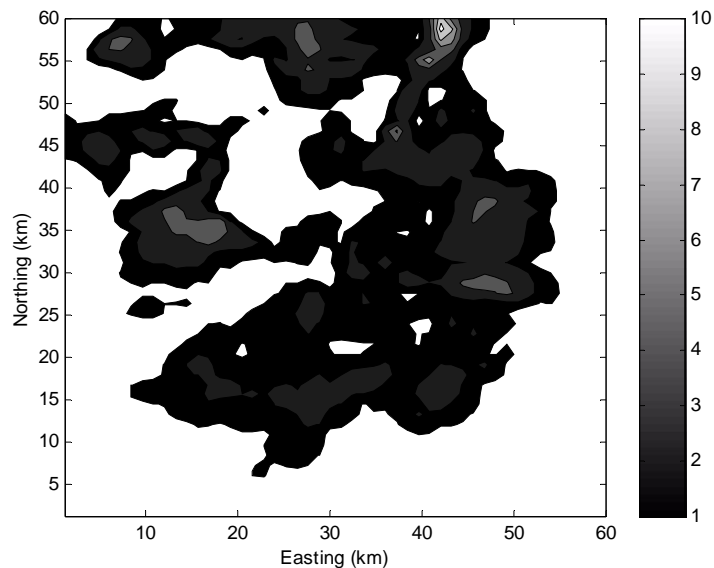
**Figure 2. Hyetographs for the 16 gauges located at the MH Watershed during the storm event of April 30<sup>th</sup>, 2002.**

## Preliminary Results

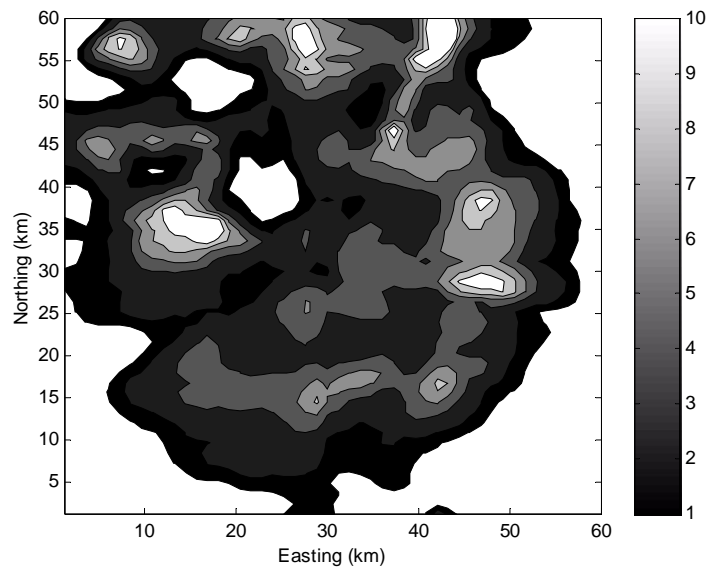
We present preliminary results using the data at 23:00 because this is the most active period of the storm. Figures 3 and 4 show the spatial distribution of rainfall intensity as inferred by XPOL radar over the 3,600km<sup>2</sup> area prior to and after image restoration, respectively. The restoration has invoked point conditioning at only one gauge (#08 located at an Easting of 26.7km and a Northing of 33km). This gauge was selected because it exhibited the highest rainfall rate (5.08mm/hr) during the time period of interest.

The efficacy of the algorithm is tested by plotting a scattergram of the rainfall intensity as inferred by XPOL radar versus the rate measured at the gauges prior and after image restoration. These results are shown in Figures 5 and 6, together with the best linear fits obtained for these scattergrams. Note that if the results were perfect, all data points would fall on the 1:1 line and exhibit a correlation coefficient of 1.0 (i.e., all points are on the best linear fit with a slope of 1:1). It should also be noted

that in Figures 5 and 6 data from only 8 out of 16 gauges are shown. Even though all information is used during the calculations, the remaining 8 gauges are excluded from the testing phase because they have recorded only trace amounts of rainfall (classified as 1mm/hr based on instrument resolution) during the time period of interest (i.e., 22:55±0:05).

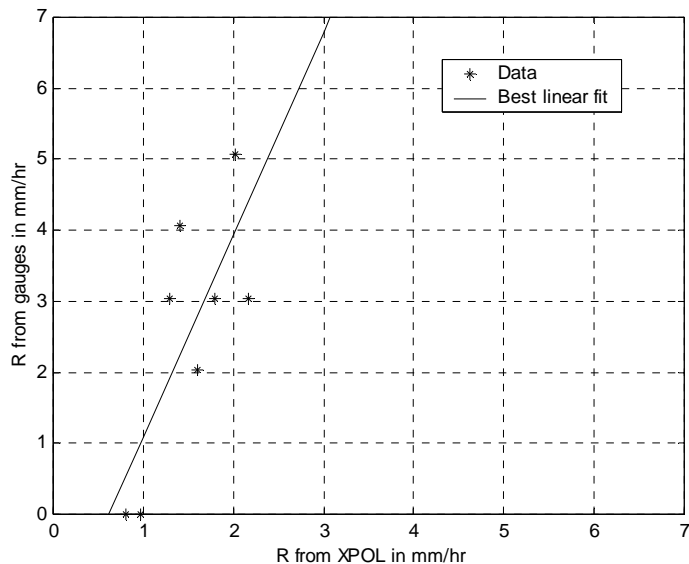


**Figure 3. Rainfall intensity (mm/hr) as inferred by XPOL radar image, averaged over 15 minutes and smoothed over a moving  $4 \times 4$ -pixel window, prior to image restoration.**

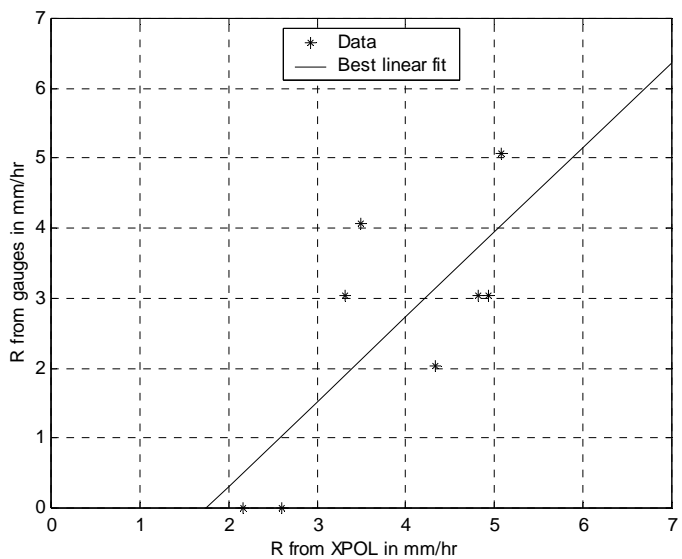


**Figure 4. Rainfall intensity (mm/hr) as inferred by XPOL radar image after image restoration.**

It is clear that there exists a noticeable bias between radar and gauge rainfall data for the radar data prior to image restoration (slope 2.85:1 and  $\rho=0.7617$ ). It is also clear that this bias is almost totally corrected after image restoration (slope 1.21:1 and  $\rho=0.7499$ ). Even though the correlation coefficient,  $\rho$ , exhibited a slight decrease, the remarkable improvement in the slope (almost equaling the ideal 1:1) more than outweighs this minor problem.



**Figure 5. Rainfall rate based on XPOL radar versus rate measured at gauges prior to image restoration.**



**Figure 6. Rainfall rate based on XPOL radar versus rate measured at gauges after image restoration.**

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