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# RADAR-RAIN GAUGE ADJUSTMENT AND ITS SENSITIVITY TO THE METHOD OF COMPARISON

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## 1. INTRODUCTION

The propagation of the radar beam away from a site is accompanied by an increase in the sampling volume and an increase of the height of the radar beam center depending on elevation angle, earth curvature and the gradient of the atmospheric refraction index. As radar range increases, reflectivity gradients are increasingly smoothed and range-related bias in radar rainfall estimates introduced (*Zawadski*, 1984). Weather radar scans have a unique spherical geometry where data resolution can differ significantly in space and time. In many hydrologic applications, radar reflectivity data are merged or compared with geospatial data that are defined using different coordinate systems, necessitating smoothing, interpolation, and/or filtering of data. Even when comparing reflectivity data from two radars sited at different locations, the differences in geometry of the two domains have to be taken into account. There are many different ways to transform radar data into grid data (e. g. square, hexagonal, truncated conical). For example, when radar rainfall data are to be used in distributed runoff modeling, they are sometimes averaged over Cartesian grids that correspond with the hydrologic model grids. Because radar rainfall products are contaminated with various types of error, questions regarding the accuracy of coordinate transformations are typically considered to be of less significance.

Simulation studies and data-based analyses demonstrate that radar range has significant influence on the accuracy of radar-estimated precipitation (e.g. *Sharif et al*., 2002; *Kitchen and Jackson*, 1993). The uncertainty of radar precipitation is also complicated by several other factors, such as, the variations in drop size distributions and the vertical reflectivity profile, and the area-point difference when radar estimates are validated against rain gauge observations (*Krajewsk*i, 1987; *Kitchen and Blackall*, 1992; *Joss and Lee*, 1995). This paper addresses issues related to areal averaging of radar estimates and their use in gauge-radar comparisons. First, a very precise method for areal averaging of radar estimates is introduced. Radar and rain gauge precipitation estimates from a field experiment were analyzed to address these and other issues. High quality data sets from NEXRAD, NCAR's S-Pol radar, and rain gauge networks were used to conduct a comprehensive comparison between the radar systems and with rain gauge observations. Total storm accumulated precipitation as recorded by rain gauges were compared to radar estimates at different spatial scales. Issues such as accuracy of interpolation, grid size and shape, and distance from the radar were examined.

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## 2. AREAL AVERAGING OF RADAR ESTIMATES

WSR-88D precipitation estimates are usually averaged on 4 km X 4 km Cartesian grids and at hourly temporal resolution. For runoff simulations, radar estimates are averaged at different spatial (typically square grids) and temporal resolutions. Spatially averaged radar products have many other applications such as ingestion into atmospheric models, multi-sensor rainfall estimation algorithms, and verification of quantitative precipitation forecasts. Computation of mean-areal radar precipitation estimates is often done haphazardly. In this section we describe a very precise method for computing mean-areal precipitation and demonstrate how the approximate methods can produce significantly different estimates.

It is common practice to compute radar rainfall estimates for Cartesian grids or an area of particular shape, by averaging rainfall estimates of all radar bins whose centers fall within the grid or area. All radar bins have the same weight regardless of how much of the radar bin area falls within the grid. This approach can introduce significant errors in several situations. For example, it is possible that just over 50% of the radar bin area falls within a particular grid and the simple interpolation scheme will assume that 100% of the area falls within the grid. Conversely, if just less than 50% of a radar bin falls in a grid, its contribution will be ignored altogether. The fact that adjacent radar bins along a ray do not have exactly the same area is always ignored in this approach. In reality, the difference in area between radially adjacent 1 km radar bins at 10 km distance from the radar is about 10%; the difference drops to about 2.5% at 40 km distance from the radar. Moreover, adjacent radar bins may report precipitation amounts that are significantly different in magnitude. It can be argued that there are many uncertainties associated with radar rainfall estimates that make these concerns look trivial, for instance: beam power distribution, side lobes, and three-dimensional averaging within the radar bin. We think precise radar rainfall interpolation for hydrologic application is more than an exercise in geometry and is warranted for many reasons, particularly if gauge-radar comparisons are to be used for adjusting radar-derived rainfall estimates. Because radar measurement volumes projected on the ground have truncated conical shapes, it is better to perform precise interpolation based on this shape, especially since precise interpolation is not very complex and does not require significant computational effort.

In the following description we use the word "radar bin" or simply "bin" to describe the volume of space contained within a radar measurement volume. When we use the term 'area' of the radar bin we refer to the projection of the radar bin onto the ground. The physical size of a radar bin is a function of the radar beam width, distance from the radar, and gate spacing of the radar. Because raw radar observations come in polar coordinates, we precisely overlay the horizontal projection of each radar bin on circular or square averaging or smoothing areas. The radar reflectivity is converted to rain rate for each radar bin. Then for each interpolation area, the amount of rainfall is computed from the radar bins that overlay the area. The area of intersection between the radar bin and the square is computed very precisely. We compute the fraction of each radar bin that falls over the smoothing area. The computations are performed precisely, e.g. if 15 bins fall partly or entirely within the smoothing area, we precisely compute the portion of each bin such that if we add the contributions from all 15 bins, they will be exactly equal to the smoothing area.

## 3. THE DATA

In the spring of 1997 NCAR's S-Pol radar was deployed as part of the Cooperative Atmospheric Surface Exchange Study (CASES97). The radar was placed about 10 km west-northwest of the Wichita, Kansas WSR-88D (KICT). Measurements were collected with both radars and a network of about 70 rain gauges were for events in May and June 1997. All rain gauges used were tipping-bucket gauges. Radar measurement resolution was 1° x 1 km for the WSR-88D and 1° x 0.15 km for S-Pol. The 1 km data for the WSR-88D are subdivided into four data gates with 0.25 km spacing, and the measured 1 km radar reflectivity value is assigned to all four gates. The scanning temporal resolution is approximately 5 minutes for the WSR-88D and less than 2 minutes for S-Pol. The S-Pol reflectivity measurements were corrected for attenuation by atmospheric gases (oxygen and water vapor) and for rainfall attenuation using the differential phase measurements. The WSR-88D are corrected for gaseous attenuation using a different algorithm. Rainfall estimates were made with the default NEXRAD Z-R relationship ($Z = 300\ R^{1.4}$) for both radars. Accumulations were made on polar grids (1° x .25 km for the WSR-88D and 1° x 0.15 for S-Pol) using measurements from .5° antenna elevation.

For a few events from CASES97 data, radar precipitation was averaged over circular and square smoothing areas of different sizes using the precise and approximate approaches. The maximum difference in computed precipitation is plotted in Figure 1 for both NCAR's S-Pol radar and NEXRAD. It is clear that this is just a sample of the magnitudes of these differences in estimated precipitation and it is possible that larger differences can result in other situations. It seems that the difference in estimated precipitation decreases with the size of the smoothing area. When we determined the ranges at which the maximum differences were computed, we found no obvious range effect on the difference between the two averaging methods. In the rest of this paper, mean-areal radar-rainfall estimates will be computed using the "precise" method. The gradients in NEXRAD rainfall estimates are smoothed by averaging over a larger bin (in the radial direction) when compared to S-Pol. This may the reason why the differences between the two averaging schemes are about twice as large for S-Pol. The approximate averaging is not true areal averaging and depends on the difference between neighboring radar bins. Thus it may lead to erroneous results especially when areas of different sizes are compared against each other.

## 4. RESULTS AND DISCUSSION

The radar sampling resolution may have a significant effect on the G-R difference. For example, *Wilson and Brandes* (1979) found that the scatter among gauge-radar comparisons for storm accumulation increases for longer sampling intervals. It is also true that the gauge-radar (or point-area) difference increases as the averaging area is increased (*Kitchen and Blackall, 1992)*. But there are many other sources for the gauge-radar difference and it is hard to assert that a smaller smoothing area should reduce gauge-radar differences. Increasing the averaging area decreases the gauge-radar difference stemming from the radar temporal sampling interval (*Kitchen and Blackall*, 1992). This may be one of the reasons why the gauge-radar bias decreases as the smoothing area increases in Figure 2. The range effect is very obvious in Figure 2 and the scatter increases with the rain gauge–radar distance. The data are for 49 rain gauges compared with S-Pol estimates. The average bias is computed from 7 precipitation events. Similar results were obtained for square smoothing areas.

In addition to different sizes of the smoothing area around the gauge, the gauge observation is also compared to the radar for the radar bin collocated with the gauge. The side length or radius of the smoothing area for the collocated radar bin is referred to as 0 in the graphs without mentioning the size of the bin. When computing the radar bias for all events, including the collocated bin, it is clear that there is less bias when the gauge observation is compared to the radar estimates from the collocated bin. For all smoothing areas in Figure 3 the bias decreases for larger smoothing areas. The bias shown in Figure 3 was computed using ΣG and ΣR from all events. It has to be noted that when individual gauge-radar ratios were computed, the collocated radar bin has the largest ratio and the average gauge-radar ratio consistently decreases for larger smoothing areas as seen in Figure 4. Figure 3 and Figure 4 represent two different bias estimators, $\Sigma G/\Sigma R$ and $\Sigma(G/R)/n$, respectively. Comparing the two figures gives an idea about the difference between the two estimators. When individual G-R ratios were examined, there is significantly more variability for the case when gauge is compared to the collocated radar bin. Some previous studies has found that the G/R estimator is log-normally distributed (*Grayman and Eagleson*, 1970) and it seems from Figure 4 that G/R distribution is also skewed in terms of the size of the smoothing area, i.e., when the number of bins around the gauge location increases that tends to result in lower values of G/R.

Another measure of the relationship between the gauge observation and the radar estimate is the correlation between the two. This was also found to be dependent on the size of the smoothing area as demonstrated in Figure 5. The lowest gauge-radar correlation was computed when the gauge is compared to the collocated radar bin, and the correlation increases with the size of the smoothing area. In Figures 2 through 5 the gauge-radar comparisons shown were for S-Pol data and the shape of the smoothing area was circular. The results for NEXRAD were similar, and similar results were also observed when the smoothing areas were square for both radars.

## 5. REFERENCES


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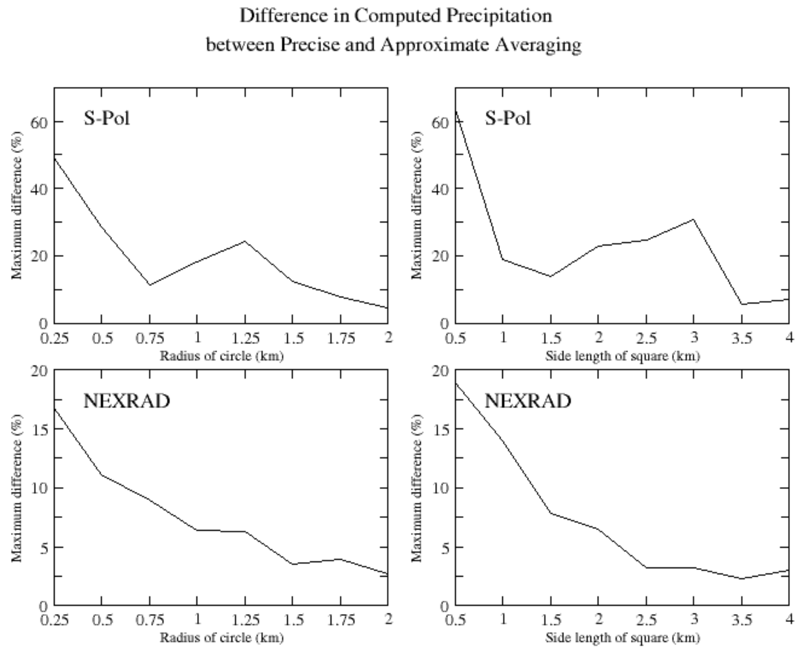


Figure 1

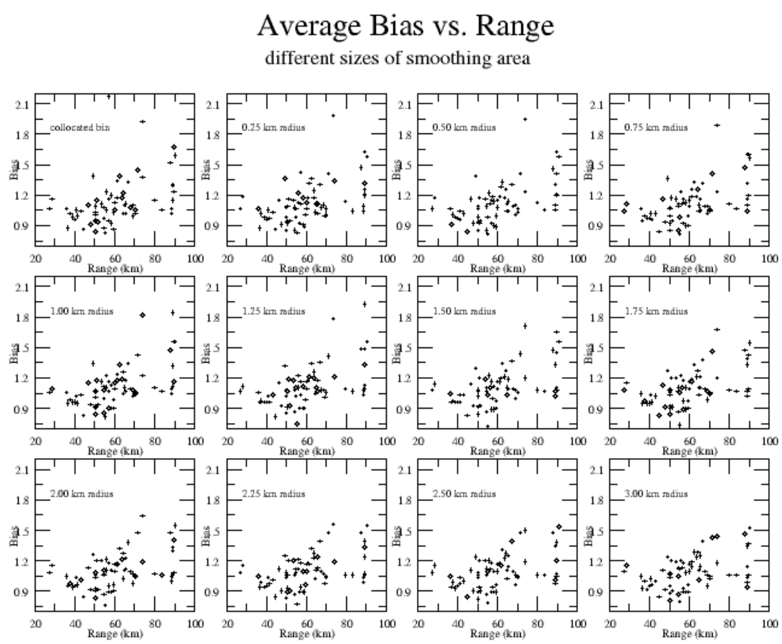


Figure 2

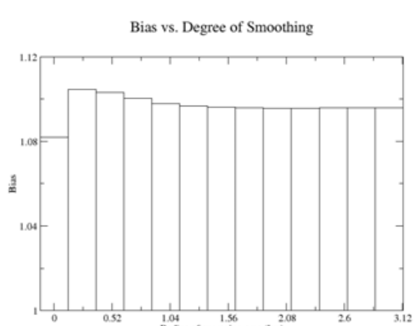


Figure 3

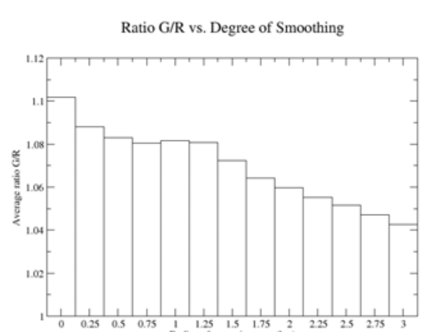


Figure 4

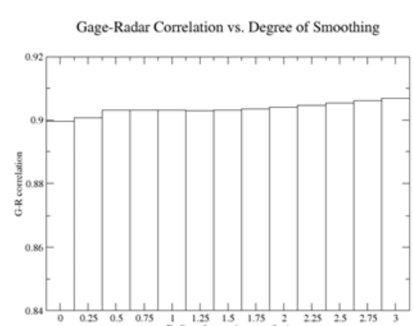


Figure 5