# Differences between Some Radar-Rainfall Estimation Procedures in a High Rain Rate Gradient Storm

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## ABSTRACT

Radar and gage data from a convective storm were analyzed with the objective of examining how much gage-estimated and radar-estimated rainfall differ in a high rainfall-rate gradient situation considering 1) the location and size of the radar contributing area, 2) whether radar-estimated rainfall was computed using maximum, average or integrated values, and 3) the radar reflectivity factor threshold. Differences exceeding a factor of 6 and 3 have been observed for individual gages and for the mean of 17 gages, respectively.

## 1. Introduction

Several investigators have combined radar and raingage data in an attempt to arrive at the best estimate of precipitation over a given area (Wilson, 1970; Brandes, 1975; Hildebrand, *et al.*, 1979). The philosophy behind this approach is to utilize the radar to specify the spatial precipitation distribution and the gages to specify the precipitation magnitude. In effect, the raingages are used to calibrate the radar. The success of this technique requires 1) that the gages measure the point rainfall accurately, 2) that the radar measures the rainfall distribution accurately, and 3) that a valid comparison can be made between the gage and radar measurement at the individual gage locations (Hildebrand *et al.*, 1979).

One technique for combining gage and radar rainfall estimates (Brandes, 1975) is to compute an adjusted radar-rainfall field through a point-by-point multiplication of each radar-rainfall data element by a distance weighted adjustment factor. The basic adjustment factor is initially calculated at the gage locations. It is computed by summing the radar-derived rainfall $R$ throughout a rainfall event utilizing some prespecified $Z$-$R$ relationship and dividing this into the gage amount $G$ to produce the ratio $G/R$. Other techniques apply the adjustment factor computed from a single gage (Wilson, 1970) or a daily areal average correction factor from a cluster of gages (Woodley *et al.*, 1975).

Different assumptions concerning radar contributing areas have been used in computing the $R$ component of the $G/R$ ratio. Areas of about 5, 25 and 130 km$^2$ were used by Hildebrand *et al.* (1979), Brandes (1975) and Wilson (1970), respectively.

The objective of this study was to examine how much the $G/R$ ratios would vary in an actual high rainfall-rate gradient situation considering the following:

1) The location and size of the radar contributing area.

2) Whether radar-estimated rainfall was computed using maximum, average, or integrated values.

3) The radar reflectivity factor threshold for average and integrated values.

## 2. Data

Radar reflectivity measurements used to estimate rainfall were collected from May through July 1976 at Miles City, Montana, as part of the Bureau of Reclamation's High Plains Cooperative Program (HIPLEX). The radar used in this study is a sensitive, narrow-beam 5 cm wavelength system which records echo data on computer compatible magnetic tape. The digitized bin volume is ~1.0° in azimuth and elevation by 0.5 km in range. The antenna scanned continuously in a volume mode of 360° in azimuth and 12° in elevation. The time interval for a complete volume scan was ~5 min, so 12 sweeps per hour were made across the gages for any given elevation angle. The radar and data processing procedures are described in Schroeder and Klazura (1978).

Radar-estimated rainfall rates $R_r$ (mm h$^{-1}$) were calculated from radar reflectivity values at 1.1° elevation angle using the familiar relationship of Marshall and Palmer (1948)

$$Z_e = 200\, R_r^{1.6}, \tag{1}$$

and were assumed applicable at ground level.

Rainfall data from 17 gages of the HIPLEX project's dense raingage network were analyzed for the 1 h time interval, 0515–0615 GMT, on 6 June 1976. The gages were located 39–79 km from the radar. This was a convective shower day (unseeded) with strong rain-rate gradients. Radar-estimated rainfall intensity gradients as high as 85 mm $h^{-1}$ $km^{-1}$ occurred. Rainfall accumulation times for the gages ranged from 15 to 60 min.

Fig. 1 is a PPI (Plan Position Indicator) display which depicts the rain-rate pattern that occurred during the beginning of the 1 h period. The rain rates were computed from the radar reflectivities using Eq. (1). This figure very clearly shows the high rain-rate gradients that existed. Positions of the 17 gages also are shown.

## 3. Methodology

In analyzing the radar data, two contributing areas were used to calculate radar-estimated rainfall. The first area was defined by a single digital radar bin (1° azimuth by 0.5 km range) which at the distances of the gages ranged from about 0.4 to 0.7 $km^2$. The other contributing area was defined by a box approximately 5 km × 5 km, with the gage location at the center. Eleven digital radar bins per radial

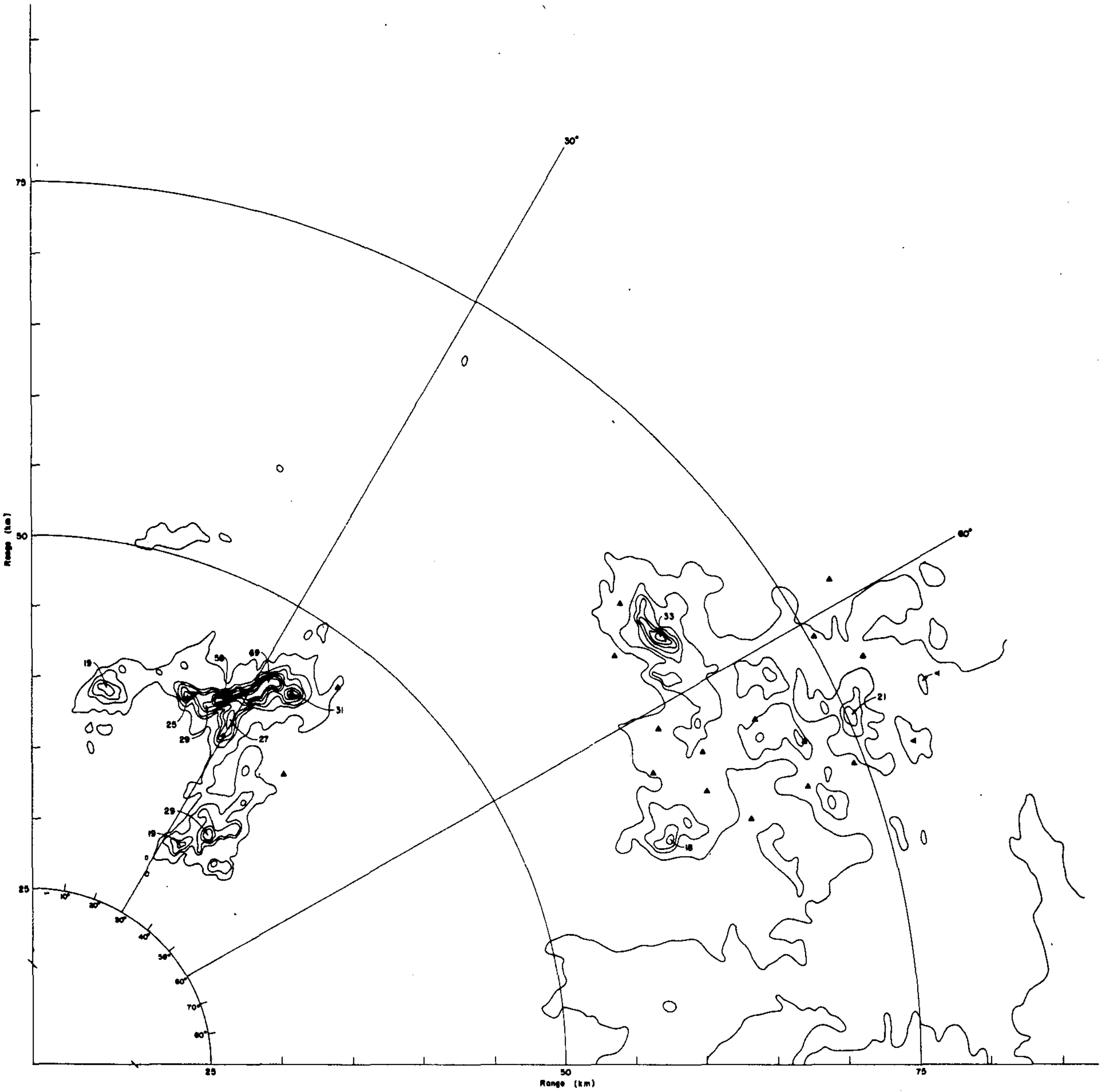

FIG. 1. Radar-estimated rainfall intensities for 1.1° elevation at 0517 GMT during a rainfall event on 6 June, 1976 near Miles City, Montana. Isopleths start at 1 mm $h^{-1}$ and the intervals are 5 mm $h^{-1}$ up to a maximum of 31 mm $h^{-1}$ (i.e., 1, 6, 11, $\cdots$ 31). Peak values exceeding 16 mm $h^{-1}$ are also shown. Locations of raingages used in the study are shown also.

(0.5 km interval) and 3–6 radials (depending on distance) were defined for each gage (33–66 bins).

The gage-estimated rainfall amount $G$ was compared with the following four estimates of radar rainfall $R$.

### *a. Radar-estimated rainfall* $R_1$ *for the radar bin directly over each gage*

This is the bin which is closest to the gage, but advection of precipitation is not accounted for. It is a logical first choice if comparison with a single bin is desired and one has no idea of how to define the horizontal transport properties of the falling precipitation.

### *b. Maximum radar-estimated rainfall* $R_2$ *for any radar bin in the 5 km × 5 km box*

This should provide some sort of upper limit from which the analyst can test the applicability or reality of the $Z$-$R$ relationship being used and also might indicate something about the effect of subcloud evaporation. One would expect that the great majority of $G/R_2$ ratios would be $<1.0$.

It is also possible that the most representative bin which would ideally be compared with the gage is located close to this bin since the advection of precipitation particles might be moving from the direction where the maximum rain rate is occurring. This would be assuming that the outflow gust emanates from regions where influences of subcloud evaporation and precipitation particle drag are the strongest.

### *c. Average radar-estimated rainfall* $R_3$ *in the 5 km × 5 km box for reflectivity factor thresholds of 10, 25, 30, and 35 dBZ*

The vagaries of advection should be ameliorated somewhat by using the averaging techniques. Thresholding should make the averaging procedure more accurate by eliminating the strong influence made from numerous bins from which precipitation never reaches the ground.

### *d. Integrated radar-estimated rain volume* $R_4$ *in the 5 km × 5 km box for reflectivity factor thresholds of 10, 25, 30 and 35 dBZ*

This is obtained by multiplying computed radar-rainfall rates by the bin area for each bin containing data above the particular threshold in the 5 km × 5 km box and summing all these over the duration of the event.

The gage-estimated integrated rain volume ($G_4$) was computed by multiplying the gage amount by the radar echo area at 1.1° elevation exceeding each threshold value within the 5 km × 5 km box.

This may be a substantial improvement over the other techniques in that the gage and radar data are made more alike. The technique allows the effective area represented by each gage to be different. Thresholding may play a more important role here than in the averaging case since both the $G$ and $R$ terms are affected.

## 4. Results

Gage-to-radar estimated precipitation ratios ($G/R$) are shown in Table 1 for each gage and each of the four methods of estimating $R$ described in the previous section. The mean and median $G/R$ ratios are also listed.

For the $G/R$ ratios based on the radar-estimated rainfall for the bin directly over each gage, i.e., $G/R_1$, there is only one case in which the radar estimate exceeds the gage estimate. The mean, median and maximum $G/R_1$ ratios are 5.0, 4.4 and 10.1, respectively.

The results are quite different for the $G/R$ ratios based on the maximum radar-estimated rainfall for any bin within ~2.5 km of the gage, i.e., $G/R_2$. There are five cases in which the radar estimate exceeds the gage estimate, and the mean, median and maximum $G/R_2$ ratios are significantly lower being 1.6, 1.5 and 3.6, respectively.

Results for the $G/R$ ratios based on the average radar-estimated rainfall in the 25 km$^2$ boxes, $G/R_3$, for the 10 dBZ radar reflectivity factor threshold are in fairly close agreement with the $G/R_1$ ratios. The mean, median and maximum $G/R_3$ ratios are 4.4, 4.1 and 11.3, respectively. However, the $G/R_3$ ratios generally drop as the threshold of radar reflectivity increases. The mean, median and maximum $G/R_3$ ratios are 3.3, 3.0 and 7.8 for the 25 dBZ threshold and 2.4, 2.6 and 5.3 for the 35 dBZ threshold.

For the $G/R$ ratios based on the integrated radar-estimated rainfall in the 25 km$^2$ boxes, $G_4/R_4$, for the 10 dBZ threshold, there is also fairly close agreement with the $G/R_1$ and $G/R_3$ (10 dBZ threshold) categories. In fact, the mean and median $G_4/R_4$ ratios are the same as the $G/R_3$ ratios (4.4 and 4.1, respectively), and the maximum is nearly the same (11.2). As the threshold of reflectivity factor increases, the $G_4/R_4$ ratios generally decrease even more than the $G/R_3$ ratios. For the 35 dBZ category the mean, median and maximum $G_4/R_4$ ratios are in close agreement with the $G/R_2$ ratios (1.7, 1.8 and 3.8, respectively).

## 5. Discussion

The primary justification for using the $G/R$ ratio as an adjustment factor to be applied to radar-estimated rainfall is that there is a definite physical relationship between the gage-estimated and radar-estimated rain. The basic assumption is that the volume of rain which is sampled by the gage is con-

TABLE 1. Gage/radar ($G/R$) ratios for rainfall over 17 gages near Miles City, Montana, on 6 June 1976 (0515–0615 GMT).

| Gage accumulation time (min) | $G$ Gage rainfall (mm) | $G/R_1$* | $G/R_2$* | $G/R_3$* Thresholds (dBZ) (10) | (25) | (30) | (35) | $G_4$*/$R_4$* Thresholds (dBZ) (10) | (25) | (30) | (35) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 60 | 6.4 | 7.4 | 1.4 | 5.9 | 3.0 | 2.3 | 2.6 | 5.8 | 3.2 | 2.8 | 2.0 |
| 60 | 2.8 | 3.9 | 0.8 | 3.3 | 1.7 | 1.4 | 1.4 | 3.4 | 2.0 | 1.0 | 0.7 |
| 45 | 15.2 | 5.1 | 1.1 | 5.3 | 3.4 | 2.7 | 2.3 | 5.2 | 3.4 | 2.8 | 2.2 |
| 30 | 0.8 | 1.9 | 0.1 | 0.4 | 0.2 | 0.2 | 0.2 | 0.4 | 0.2 | 0.2 | 0.1 |
| 15 | 1.3 | 4.2 | 0.7 | 3.3 | 1.4 | 1.0 | 0.9 | 3.1 | 1.3 | 0.9 | 0.6 |
| 30 | 0.8 | 4.2 | 1.0 | 2.2 | 3.2 | 2.2 | 1.4 | 1.7 | 0.7 | 0.5 | 0.3 |
| 45 | 5.3 | 10.1 | 3.6 | 11.3 | 6.4 | 16.7 | — | 11.2 | 3.8 | 1.6 | — |
| 45 | 5.8 | 4.4 | 1.9 | 4.1 | 3.6 | 3.0 | 2.7 | 4.1 | 3.7 | 3.2 | 2.1 |
| 60 | 15.7 | 7.7 | 3.4 | 7.8 | 7.8 | 6.5 | 5.3 | 7.8 | 8.0 | 6.9 | 3.7 |
| 30 | 4.6 | 0.5 | 0.2 | 1.0 | 0.9 | 0.7 | 0.6 | 1.0 | 0.9 | 0.7 | 0.6 |
| 45 | 5.1 | 5.6 | 1.5 | 4.4 | 3.0 | 3.0 | 3.4 | 4.5 | 3.3 | 3.1 | 2.2 |
| 30 | 5.8 | 8.9 | 2.0 | 7.0 | 4.9 | 4.9 | 2.9 | 7.2 | 5.5 | 4.4 | 2.8 |
| 45 | 12.4 | 5.0 | 2.7 | 5.0 | 5.0 | 5.3 | 4.9 | 5.0 | 4.6 | 4.3 | 3.8 |
| 60 | 3.0 | 6.2 | 1.8 | 4.5 | 3.4 | 3.4 | — | 4.4 | 2.7 | 1.9 | — |
| 45 | 7.4 | 2.5 | 1.6 | 3.1 | 3.1 | 3.0 | 2.8 | 3.1 | 2.7 | 2.2 | 1.8 |
| 60 | 7.6 | 3.3 | 1.2 | 2.5 | 2.5 | 2.6 | 2.7 | 2.5 | 2.3 | 2.1 | 1.7 |
| 60 | 6.3 | 3.9 | 1.5 | 3.8 | 3.0 | 2.7 | 2.6 | 3.5 | 2.4 | 1.8 | 1.5 |
|  | Mean $G/R$ | 5.0 | 1.6 | 4.4 | 3.3 | 3.6 | 2.4 | 4.4 | 3.0 | 2.4 | 1.7 |
|  | Median $G/R$ | 4.4 | 1.5 | 4.1 | 3.0 | 2.7 | 2.6 | 4.1 | 2.7 | 2.1 | 1.8 |

* $R_1$ is the radar-estimated rainfall calculated by using the radar bin over the gage at 0.8° elevation.

* $R_2$ is the radar-estimated rainfall calculated by using the radar bin with maximum radar reflectivity within a 5 km × 5 km area surrounding gage (0.8° elevation).

* $R_3$ is the radar-estimated rainfall calculated by using the average value in the 5 km × 5 km area surrounding gage (0.8° elevation).

* $R_4$ is the radar-estimated rainfall calculated by using the integrated rain volume in the 5 km × 5 km area surrounding gage (0.8° elevation).

* $G_4$ is the gage-estimated rainfall calculated by multiplying gage amount by radar echo area exceeding each threshold value (0.8° elevation).

tained within the volume of rain sampled by the radar. The ideal situation is to compare the most representative radar bin with the gage. However, finding the most representative bin can be an extremely difficult, if not impossible, task because an accurate knowledge of the horizontal displacement and vertical sorting of precipitation particles as they fall and time corrections to account for the time interval between radar detection and gage detection is required. In the strong outflow wind fields associated with high-gradient convective showers, horizontal displacements of precipitation can be significant. Brandes and Sirmans[1] estimated that displacements of 2–5 km per kilometer of fall are to be expected for a horizontal wind of 20 m $s^{-1}$. To compute the trajectory which the precipitation particles followed requires one to know the environmental wind profile and drop sizes. The wind field associated with convective precipitation usually is quite complicated with large spatial and temporal changes. The capability to calculate this wind field generally is nonexistent. Hildebrand *et al.* (1979) tried to allow for precipitation advection by considering winds from a regional upper air sounding, but found these winds to be inadequate. Even if one is fortunate enough to locate the proper bin, a comparison is being made between a cross-sectional area which usually exceeds 500 000 $m^2$ and the cross section of the gage which is less than 0.05 $m^2$. In a low-gradient, more uniform rainfall rate situation, it probably is not too serious to correlate with a radar bin which is close to but not exactly the correct one. But in a high-gradient situation, such as the one looked at, the results may have very large errors.

Large reflectivity gradients cause another type of uncertainty to further complicate the problem. Radars with either linear or logarithmic response tend to underestimate the actual mean reflectivity in regions of reflectivity variations. The errors are larger in radars with logarithmic response (such as the one that collected data for this study). Rogers (1971) estimated that the error for logarithmic radars can amount to 3 dB in conditions of moderately strong reflectivity variations (20 dB per measurement cell) and to 6 dB in extremely variable conditions (30 dB per measurement cell). The maximum reflectivity variation observed in this analysis was about 20 dB per averaged range interval.

Additional errors in radar-rainfall estimation can occur. Hildebrand *et al.* (1979) emphasized that rain evaporation between the rain detection level and the

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[1] Brandes, E. A., and D. Sirmans, 1976: Convective rainfall estimation by radar: experimental results and proposed operational analysis technique. *Preprints Conf. Hydrometeorology*, Ft. Worth, Amer. Meteor. Soc., 54–59.

ground may be a very important factor. In fact, they concluded that evaporation was one of the primary reasons for the lack of positive results in their technique of combining raingage and radar data to compute area-mean convective rainfall over eastern Montana. They used radar-rainfall thresholds in an attempt to correct for evaporation and found that this technique improved comparisons between the gage-radar and gage-only analyses. The comparison between gage- and radar-estimated rainfall in the present study also was improved through the use of radar-rainfall thresholds.

Another potential error source can occur when the radar measures the reflected power from ice particles while the gage collects rain (melted ice). The echo power received from a region containing ice particles can be higher or lower than that received from an all water region depending on various factors including the size of the ice particles and the amount of water coating on their surfaces. Ice probably was not a contributing factor in the present investigation. In the range and elevation limits that were used the radar beam was always sensing in a region of the atmosphere whose temperature exceeded +5°C.

Wilson and Brandes (1979) listed the sources of some other errors that can occur. These included beam blockage by obstacles close to the radar site, anomalous propagation (bending) of the radar beam, the build-up of precipitation films on the radome, and attenuation by precipitation, cloud and atmospheric gases. No significant effects by any of these factors occurred in this study.

## 6. Conclusions

This study has shown that the *G/R* ratios can vary significantly depending on the assumptions used. It is logical to expect that the estimates of precipitation over an area which is computed through the use of the various gage-radar rainfall estimation techniques would also vary by a significant amount. Therefore, the results suggest that an improved method of combining gage and radar data is possible and will produce better rainfall estimates over large areas. The problem which needs to be resolved is the identification of the best technique to use in computing the *G/R* ratios.

It is beyond the scope and capability of the present analysis to be able to conclude definitively which technique is best. This is precluded because of the limited date set analyzed and because of the absence of positive truth (i.e., the knowledge of the location of the most representative radar bin). However, the strong signal which has emerged from this study at least serves as sufficient justification for the statement of some general comments and suggestions which may be beneficial to those who will pursue this problem further.

- Without some type of comparative analysis, one cannot know whether improvements in *G/R* ratios (i.e., values closer to 1.0) necessarily will lead to better rainfall estimates. In other words, the optimum technique for producing representative values of *G/R* is not necessarily the one which produces values that are closest to unity.
- If wind information is available at each gage location, it may be possible to make a reverse trajectory analysis and identify the most representative radar bin for each averaging time period.
- If it is not possible to isolate the proper single radar bin with which to compare the gage measurement, it probably is best to use either the averaging or integrating method with a reflectivity factor threshold. The radius chosen should consider the maximum expected horizontal drift of precipitation particles from the vertical point at which they are detected by the radar to the point at the surface where they finally land. The reflectivity factor threshold used should be the minimum in which precipitation just survives subcloud evaporation and can be detected at the surface.

Wilson and Brandes (1979) studied the averaging technique and had favorable results. They concluded that differences between point gage and radar observations can be minimized if the radar totals are spatially averaged about the gage site. Although an averaging radius that minimizes point gage/radar differences exists, they found that the specific radius selected is not critical, since the average error changes slowly near the optimum radius.

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