## P2.4 CONSIDER THE WIND DRIFT EFFECTS IN THE RADAR-RAINGAUGE COMPARISONS


Lei Feng  Ben Jong-Dao Jou*  T. D. Keenan

*National Science and Technology Center for Disaster Reduction, Taipei County, R.O.C*

*National Taiwan University, Taipei, R.O.C*

*Bureau of Meteorology Research Centre*



**Abstract**

Most radar-raingauge comparisons follow a major assumption that the precipitation observed aloft impacts the surface directly below the volume sampled by the radar. However, it is well known that rain may be advected laterally considerable distances by the horizontal wind. This is a serious problem when high resolution urban hydrology model are utilized as an input parameter. A new comparison method considering the horizontal displacement is proposed which is to find an optimal horizontal displacement of the radar data above the surface raingauges. After the horizontal adjustment, the radar estimated rain rates aloft will have maximum correlation with the rain rates of surface raingauges. The main assumption is that the precipitation observed by radar within the same sweep will fall down to the ground in the same time and shift with same horizontal displacement. Three convective events in Darwin, Australia were analyzed; the analysis shows that excellent results could be achieved using KDP-based rain-rate estimator by C-band polarimetric radar.* The normalized error (normalized bias) of radar-raingauge comparisons for the traditional method is 43.9% (-14.1%) and for the optimal method is 27.0% (-10.7%). It's about 17% improvement of the normalized error when the optimal method is applied.


## 1. Introduction

A radar-raingauge comparison is a complex problem. It is recognized that the compared measurements are of different characters: raingauge accumulates continuously value of point rainfall rate while radar-derived values correspond to a volume-averaged rainfall rate. They are different types of measurement. There are various error sources, such as space-time smoothing of radar and gauge data, drifting by low-level winds, evaporation and drop-size sorting, etc. There still has a time delay between the radar and the raingauge measurements. For a rapidly changing rainfall rate, this time delay introduces a further discrepancy between the two measurements (Zawadzki 1975, 1984). It is recognized that the radar-raingauge comparison is acceptably good when total amounts over several hours of rainfall are considered. Instantaneous comparisons show great discrepancies due to the various problems in conversion from radar observations to rain rate and also due to the different characters of the two measurements. However, surface raingauges are always used for evaluating the capability of radar rain rate estimators.

Most hydrological applications, a major


* *Corresponding author address:* Ben. J.-D. Jou, Dept. of Atmospheric Sciences, National Taiwan University, 61 Lane 144 Kee-Long Rd. Taipei, Taiwan, R.O.C; e-mail: jou@as.ntu.edu.tw

assumption is made that the precipitation observed aloft impacts the surface directly below the volume sampled by the radar (Lack and Fox, 2004). However, it is well known that rain may be advected to a considerable distance laterally, implying that rainfall entered into distributed hydrological models will be inaccurate no matter how accurately the rain is measured aloft. In extreme cases, rain may be observed above one catchment and actually fall in another. As moves are made toward more accurate precipitation retrievals (such as using polarimetric radar) and higher resolution applications (such as urban hydrology model) this problem has been received more attentions.

In hydrological applications of weather radar, incorporating surface rainfall fields accurately, not only intensity but also spatial accuracy, is of key importance. Ignoring the effects of wind-drift on falling precipitation could cause errors in predicted streamflow, and other variables important to hydrological studies (Lack and Fox, 2004). The first publication that identifies the problem of wind drift is found in Gunn and Marshall (1955). They identify the parabolic trajectory of raindrops in a constant wind shear environment, and allude to the possibility that the distances along the ground could be quite large from the original location of the droplet. A more recent reference to wind drift and urban hydrology comes from Collier (1999).

Bolen et al. (1998) described an approach similar in principle to Aydin et al. (1987). The objective procedure for locating an elliptically shaped optimal area which minimizes the root mean square (rms) error difference between $R(K_{DP})$ and gauge rain rate over an appropriate time interval. The dimensions of the ellipse are obtained from the spatial correlation structure of the rms error field. This type of methodology is based on the assumption that the $R(K_{DP})$ rain-rate estimator is essentially unbiased. Algorithms based on specific differential phase shift ($K_{DP}$) are relatively insensitive to drop size distribution (DSD) fluctuations than reflectivity ($Z_H$) based estimator. Use phase based estimators also offer several practical advantages (Chandrasekar et al. 1990; Zrnic and Ryzhkov 1996).

Lack and Fox (2004) described a series of experiments based on real data where in the advection of the precipitation below the radar sampled volume is estimated using Doppler radar determined wind fields. Their experiments show that even at standard resolutions of 2 km the error can be extensive, and at higher resolutions and greater ranges (higher beam elevations) the errors become very large. Errors are assessed using different Z-R relationships and resolutions as high as 0.5 km. Their results show that as horizontal resolution is increases, the errors become more significant within the domain.

This paper describes a method to find an optimal vector of horizontal displacement from a density raingauge network and radar estimated rain rate in the same sweep. The method is based on choosing the maximum cross-correlation between the surface rain rates measured by raingauges and the rain rates estimated by radar. Three convective events were analyzed with rain rates less than 110 mm $h^{-1}$, the analysis shows that excellent results could be achieved using $K_{DP}$-based rain-rate estimator by C-band polarimetric radar. The data sets are described in the next section. The methodology is described in section 3. The analysis results of these three convective events shows in section 4. The discussion and summary are in the last section.

**2. Data sets**

During the summer of 1999, the Australian C-band polarimetric meteorological radar (C-POL) located near Darwin, Australia, and operated by the Bureau of Meteorology Research Center (BMRC). Standard variables extracted include horizontal reflectivity ($Z_H$), radial velocity ($V_r$), spectral width ($\sigma_v$), differential reflectivity ($Z_{DR}$), total propagation differential phase shift ($\Phi_{DP}$), and zero lag correlation coefficient [$\rho_{hv}(0)$]. The system characteristics of C-POL radar can be found in Keenan et al. (1998). In the analysis period, C-POL was operated in volume scan mode with 17 levels every 10 minutes. The radius of observation is 144 km with 300 m range resolution and 1.4 degree azimuth resolution. The lowest elevation angle is 0.5 degree and is use to estimate the radar rain rates.

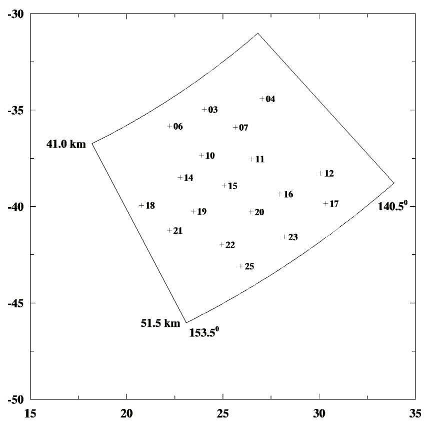


Fig. 1 The surface raingauge network located in Darwin, Australia. The C-Pol radar was located at origin point.

The surface raingauge network as illustrated in Fig. 1 consists of 18 raingauges within an area of about 100 km$^2$ which is located about 40 km southeast of radar. The gauges are 203 mm diameter tipping bucket type and the time of accumulation of 0.2 mm of rainfall is recorded. The gauges are routinely calibrated and strict data quality control procedures were used to reject faulty gauge data (May et al. 1999). For each gauge, 1-min rain rates were available as a time series.

The lowest elevation angle data is used to estimate the radar rain rates by a phase based estimator $R(K_{DP})$. Because the phase based estimator is less sensitive for small rain rates, in such situations the $R(Z_H)$ is used. If radar data is satisfied the thresholds ($Z_H$ > 30 dBZ and $Z_{DR}$ > 0.2 dB and $K_{DP}$ > 0.02 °km$^{-1}$) then the radar rain rate is estimated by R ($K_{DP}$), otherwise the $R(Z_H)$ is used. The coefficients of the $K_{DP}$-R and $Z_H$–R relations are adopted directly from Bringi et al. (2001b),

$$R(K_{DP}) = 32.4 K_{DP}^{\;0.83} \qquad (1)$$

$$R(Z_H) = 0.015 Z_H^{\;0.734} \qquad (2)$$

here, the rain rate in mm h$^{-1}$, $K_{DP}$ in °km$^{-1}$, and $Z_H$ in mm$^6$m$^{-3}$. The reflectivity is corrected for attenuation effects using a self-consistent, constraint-based method (Bringi et al. 2001a). In this algorithm, the adaptive $K_{DP}$ data are also available.

The time of radar observation ($t_{rad}$) is used as a reference time for the radar – raingauge comparisons. The rain rate of each gauge is averaged with three minutes interval from ($t_{rad}$ + $t_{lag}$– 1.5 ) to ($t_{rad}$ + $t_{lag}$ + 1.5 ), where $t_{lag}$ is the time lag that the precipitation needs to fall down to the ground. After the horizontal offset adjustment, the radar rain rates are interpolated to the position of each raingauge using the Cressman (1959) technique.

Three convective events are analyzed. The analysis periods of these 3 cases are 0510-0710 LST 15 Jan. 1999 (case 1), 1050-1230 LST 1 Mar. 1999 (case 2) and 0130-0920 LST 17 Mar. 1999 (case 3), respectively.

**3. Methodology**

For a precipitation system, especially for convective type, there are many factors which will change the vertical profile of the rain rates such as updraft, downdraft, coalescence, drop breakup, accretion, evaporation, and et al. The horizontal wind between the precipitation and ground can also distort the pattern of precipitation when falling down. In general, the rain rates observed aloft are different to the rain rates on the ground. It is very difficult to find the place of precipitation aloft such as observed by radar where the rain will fall into the specific surface raingauge. In order to simplify the question, we make some assumptions. The main assumption is that a portion of precipitation observed by radar within the same sweep will fall down to the ground in the same time and precipitation is shifted with same horizontal displacement and the rain rates of the precipitation are maintained in the falling period. By the above assumption, the pattern of rain rates aloft can be found on the ground with a horizontal displacement. Actually, precipitation will not meet the above assumption, the bigger drops aloft will fall down more quickly and have less horizontal displacement than smaller drops. The different high in the PPI scan, vertical wind shear, precipitation evolution in falling period and other factors all can distort the rain rate pattern. In fact, we don't really care what kind of the wind pattern in detail. We only take the final correlation between radar rain estimation and surface rain gauge data to identify the horizontal displacement.

A pre-defined area of radar data which covered all surface raingauges was moved within a square window (8 km x 8 km), the cross-correlation coefficient was calculated between the time lagged (1.5 minute) surface rain rates of the gauges and the space shifted radar rain rates. A two-dimensional correlation field was produced. The distance from the point of maximum correlation to the center of the square window was defined as "optimal vector" of the horizontal displacement and this procedure of radar-raingauge comparisons was called as "optimal offset method".

For a particular sweep, it needs to estimate the falling time of the precipitation. In our case, the lowest elevation angle (0.5 degree) of radar observations was used, the gauge network located about 40 – 50 km southeast of the radar site. A falling time was estimated roughly, considering an average height 500 m, and 5 m/s terminal velocity (for the 1.3 mm diameter rain drop); the falling time is about 100 seconds. For convenience the 1.5 minute is used. The next step is to calculate the correlation coefficients between the rain rates estimated by radar and the time lagged rain rates measured by raingauge in the with different offset situations within the square window. The point of maximum correlation coefficient for this particular sweep is then determined subjectively.

A demonstration to find the optimal vector is showed at Fig. 2. Fig. 2 shows the correlation coefficient field and the standard deviation field of the radar-gauge pairs. The pre-defined area of radar data are shifted in X- and Y-direction with 200 m interval and within ±4 km range in each direction. Radar rain rate is interpolated by the Cressman scheme with 0.8 km influence radius. The vector show in the Fig. 2 is the optimal vector defined subjectively. Only when gauge rain rates greater than 1 mm $h^{-1}$ and number greater than 3 stations the correlation coefficient field was calculated. The rain rates in Fig. 3 are estimated by $R(K_{DP})$ estimator, the numbers plot beside the heads of the arrows are surface rain rates of each raingauges with 1.5 minute time lag compare with radar observation time. The vectors in the Fig. 3 are the same vector pre-defined in the Fig. 2 which mean that the rainfall aloft (observed by radar) falls down from the end points of the arrows to the ground on the head points of the arrows (positions of surface raingauges).

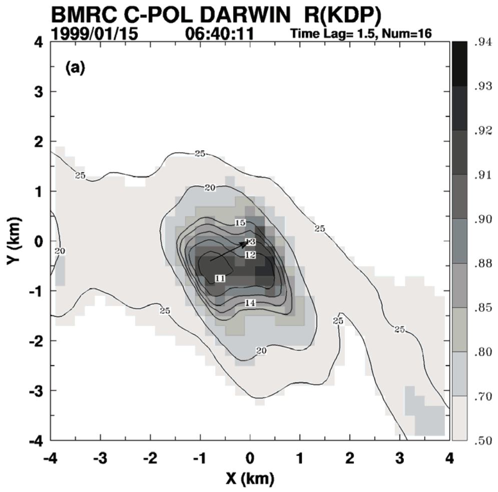


Fig. 2 The correlation coefficients (shaded) and standard deviations (contour lines) of radar-gauge pairs in the 8 km x 8 km domain at 06:40 15 Jan. 1999. The arrow represents the optimal vector.

There are 89 volume scan of radar data meet the criteria but only 39 optimal vectors can be clearly defined. We find that in these 39 volume scans each one exists at least one rain rate of raingauge great than 10 mm $h^{-1}$ (reach the convective type rain rate ), most of the rejected volumes are stratiform rain type in the domain of gauge network.

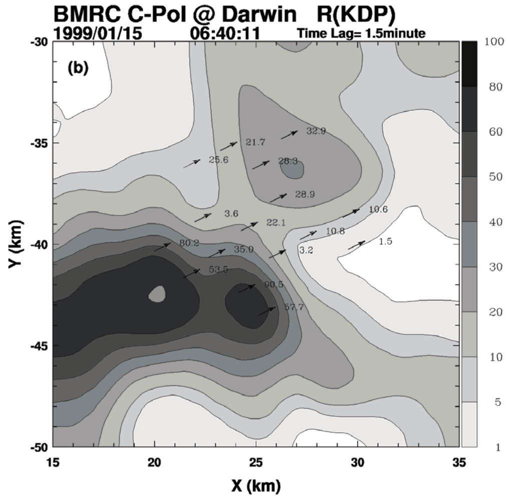


Fig 3 The rain rates estimated by R(KDP) at 06:40 15 Jan. 1999. The arrows are the optimal vector defined in Fig 2. The raingauges are at the head points of the arrows, the numbers beside the raingauges are surface rain rates.

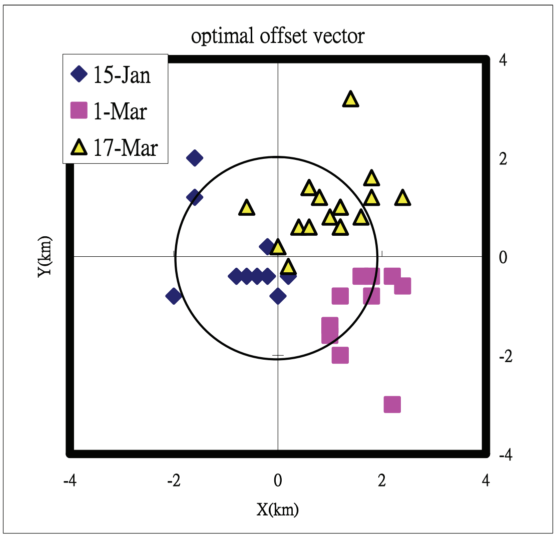


Fig. 4 The diamond, square and triangle are the optimal vectors for the case 1 through 3, respectively. The circle is plot with 2 km radius.

## 4. Radar-gauge comparisons

The 39 optimal offset vectors for these three rainfall events are plot in the Fig. 4, and can see the most optimal vectors (horizontal displacements) are less than or around 2 km. This is a reasonable horizontal displacement for convective rain. For a 2 km displacement and 1.5 minute falling time, the corresponding horizontal wind speed is about 22 m/s. Since the rain rate of raingauge is 3 minutes averaged, the averaged rain rate contains the information between the ±1.5 minutes. If we add the 1.5 minute to the falling time, then the 2 km horizontal displacement need about 11 m/s wind speed. If the terminal velocity of rain drop is 1 m/s (for 0.3 mm rain drop), it needs 500 seconds of falling time from 500 m height, the corresponding horizontal wind speed is 4 m/s for 2 km horizontal displacement.

In Fig. 4, the optimal vectors are gathered in 3 groups, the average of the grouped optimal vectors is close to the moving direction of convective system. However, there are few optimal vectors departure from the clusters. For case 1, there are two optimal vectors (05:10 and 05:50) far away from the cluster. In these cases the raingauges are in front of the convection line. By checking the radial velocity data the wind above these raingauges was blowing from northwest. When the convection line arrived the gauge network, the wind direction above the raingauge network changed from northwestly to southwestly. In general, the optimal vectors are close to local wind direction and we believe the optimal vectors are very close to the vertical displacements of rainfall. It need more research to verify this point and are in the future works.

It is interesting to compare with traditional method and optimal method. The traditional method is using the radar estimated rain rates just above the raingauges. The gauge rain rates are 3 minute average and the central time is same with radar observation time. The radar rain rates are interpolated using the Cressman scheme with 0.8 km influence radius. The optimal method is in the same manner but the time of gauge rain rate are lagged 1.5 minute, and radar estimated center are shifted with a displacement of an optimal vector. The radar-raingauge comparisons of the case 1 - 3 using the traditional method and optimal method are plot in Fig. 5 (a) - (f), respectively. From these figures, the improvements are obviously when the optimal method is applied. For case 1, the correlation coefficient increases from 0.78 to 0.93 and standard deviation decreases from 12.4 mm $h^{-1}$ to 7.6 mm $h^{-1}$. For case 2, the correlation coefficient increases from 0.84 to 0.97 and standard deviation decreases from 11.0 mm $h^{-1}$ to 5.7 mm $h^{-1}$. For case 3, the correlation coefficient increase from 0.75 to 0.87 and standard deviation decrease from 4.2 mm $h^{-1}$ to 3.1 mm $h^{-1}$.

In order to compare with the results of areal rainfall estimator using differential propagation phase by Bringi et al. (2001b), here after call $AR_{CSU}$ estimator, following their concept, the normalized error (NE) is defined here as

$$NE = \frac{\left(\frac{1}{N}\right)\sum_{i=1}^{N}\left|R_{radar} - R_{gauge}\right|}{\left(\frac{1}{N}\right)\sum_{i=1}^{N} R_{gauge}} \qquad (3)$$

and the normalized bias (NB) as

$$NB = \frac{\left(\frac{1}{N}\right)\sum_{i=1}^{N} R_{radar} - R_{gauge}}{\left(\frac{1}{N}\right)\sum_{i=1}^{N} R_{gauge}} \qquad (4)$$

The normalized error (NE = 25.8%) and normalized bias (NB = -4.6%) of optimal method for case 1 are quite close to case of 18 Feb. 1999 in

Bringi et al. (2001b) (see their Fig 5).

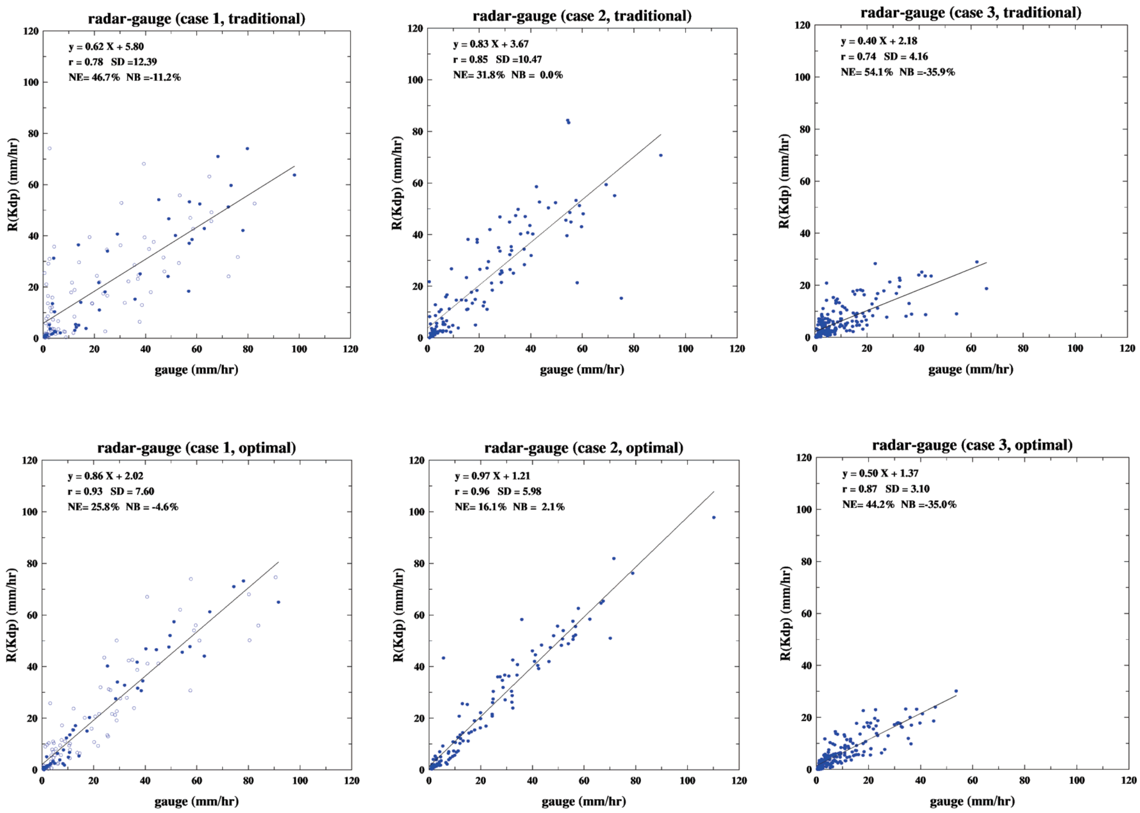


Fig. 5 The scatter plots of radar-gauge comparisons using traditional and optimal method for three cases. The circles in (a) and (b) represent the rain rates of the cell in front of convective line, and the dots represent the rain rates of the convective line.

Note that the radar-gauge comparisons of their case are area averaged (100 km$^2$) and our case is radar-single raingauge comparisons with horizontal displacement adjustment. Bringi et al. (2001b) also calculated the storm total rain accumulation (based on samples of radar $\overline{R}$ and gauge network $\overline{R}_g$ spaced 10 min apart) for 12 events; the normalized error is 14.1% and normalized bias is 5.6% for the $AR_{CSU}$ estimator. In the optimal method of case 2, the normalized error is 15.4% and normalized bias is 1.3% this is close to storm total rain accumulation of the $AR_{CSU}$ estimator. As mention above, in case 1 a single convective cell in front of the convective line. If we remove the data of this cell, the normalized error (17.4%) and normalized bias (-6.7%) of case 1 are close to case 2. The results imply that if the horizontal displacement is processed correctly, the accuracy of radar rain rate estimation for single raingauge (or 2 km$^2$ for radar rain rates) which is in the same order of 100 km$^2$ area average (space smoothing) or storm total accumulation (time and space smoothing).

For more accurate precipitation retrievals and higher resolution applications such as urban hydrology model, the space smooth of radar rain rate will be another problem need to consider in the near future. We use the same data sets to test the influence radius effects. Remember that the optimal vector finding procedures are using the 0.8 km influence radius, here do not redo the optimal vector finding procedures when radar-gauge comparisons using different influence radiuses. The results of correlation coefficients and normalized errors are in table 1 and 2, respectively. In general, the radar-raingauge comparisons by traditional method, the lager influence radius get larger correlation coefficients and smaller normalized errors, except 0.4 km. This can be explained as radar-raingauge discrepancies are reduced by larger space smoothing. In contrast, the radar-raingauge comparisons by optimal method, the larger influence radius get smaller correlation coefficients and larger normalized errors. This means that if the correct positions of radar estimating rain rates are used, to extend the average size are to introduce more uncertainties and make the results worse.

Table 1 Correlation coefficients of radar-gauge comparisons by traditional method and optimal method with different influence radiuses.

| r | 15-Jan-99 | | 1-Mar-99 | | 17-Mar-99 | | 3 cases | |
|---|---|---|---|---|---|---|---|---|
| Radius | traditional | optimal | traditional | optimal | traditional | optimal | traditional | optimal |
| 0.4 km | 0.83 | 0.92 | 0.88 | 0.99 | 0.69 | 0.90 | 0.84 | 0.93 |
| 0.6 km | 0.76 | 0.93 | 0.81 | 0.98 | 0.76 | 0.87 | 0.80 | 0.94 |
| 0.8 km | 0.78 | 0.93 | 0.84 | 0.97 | 0.75 | 0.87 | 0.81 | 0.93 |
| 1.0 km | 0.79 | 0.93 | 0.85 | 0.96 | 0.74 | 0.87 | 0.82 | 0.93 |
| 1.2 km | 0.79 | 0.92 | 0.86 | 0.96 | 0.74 | 0.85 | 0.82 | 0.92 |
| 1.5 km | 0.79 | 0.92 | 0.87 | 0.95 | 0.73 | 0.83 | 0.82 | 0.91 |

Table 2 Normalized error (NE) of radar-gauge comparisons by traditional method and optimal method with different influence radiuses.

| *NE* | 15-Jan-99 | | 1-Mar-99 | | 17-Mar-99 | | 3 cases | |
|---|---|---|---|---|---|---|---|---|
| Radius | traditional | optimal | traditional | optimal | traditional | optimal | traditional | optimal |
| 0.4 km | 0.72 | 0.86 | 0.96 | 1.03 | 0.49 | 0.59 | 0.78 | 0.88 |
| 0.6 km | 0.74 | 0.93 | 0.90 | 1.00 | 0.51 | 0.57 | 0.76 | 0.90 |
| 0.8 km | 0.74 | 0.90 | 0.92 | 1.00 | 0.50 | 0.58 | 0.77 | 0.89 |
| 1.0 km | 0.75 | 0.89 | 0.92 | 0.99 | 0.50 | 0.57 | 0.77 | 0.88 |
| 1.2 km | 0.74 | 0.88 | 0.92 | 0.99 | 0.49 | 0.55 | 0.77 | 0.87 |
| 1.5 km | 0.74 | 0.87 | 0.91 | 0.97 | 0.48 | 0.53 | 0.76 | 0.86 |

**5. Discussion and summary**

It is recognized that the relation between measured radar rain rate and surface rain rate is highly complex; it depend on a number of physical factors, the effects of which may vary significantly from one storm to another. Austin (1987) has discussed many physical factors that influence the relation between measured radar reflectivity and surface rainfall through detailed comparisons of radar and raingauge measurements. These factors include natural differences in raindrop-size distributions, enhancement of radar reflectivity by presence of hailstones or melting snow, diminution of reflectivity by downdrafts, and low-level changes in rainfall rate caused by accretion or evaporation. Even if there are no actual errors in either gauge or radar measurements, there might be significant discrepancies between indicated amounts of rainfall at any given gauge site because of differences in sampling modes. The radar samples almost instantaneously a volume of atmosphere which has a surface projection of several square kilometers, and measurements are repeated at interval of several minutes. The gauge accumulates continuously rain falling on an area which is generally much smaller than a square meter. At any given instant, rainfall intensity often varies significantly over distances of less than a kilometer, while at any given point it may change during time intervals of a minutes or less.

This paper is an exploration on a new method for attempting to correct the horizontal displacement of precipitation observed by radar. We make some assumptions to simplify the question: 1) a portion of precipitation (100km$^2$) observed by radar within the same sweep will fall down to the ground simultaneously; 2) the precipitation maintains the strength and the space distribution in the falling period; 3) the pattern of rain rates aloft can be found on the ground with a horizontal displacement. By these assumptions, we should expect that after moving the radar data by an offset vector the radar-raingauge pairs will have very high cross correlation and very low standard deviations if the rain rate estimator is unbiased. The proposed method here is to find an optimal vector by search the maximum cross correlation and minimum standard deviation of the radar-gauge pairs in the different shifted situations.

Three convective events during the summer of 1999 were analyzed; the BMRC/NCAR C-POL radar was used to estimate rain rates. The raingauge network consists of 18 gauges within a 100 km$^2$ area located about 40 km southeast of the radar site. Only 39 optimal vectors can be clearly defined subjectively from the 89 volumes scan data set. After the optimal method is applied, the radar-raingauges comparisons improved greatly. With optimal offset vector adjustment, the normalized error (25.8%) of case 1 is close to the results of the area averaged result by the $AR_{CSU}$ estimator. The normalized error (15.4%) of case 2 is close to the result of storm total rain accumulation by the $AR_{CSU}$ estimator. If combines these three cases, the normalized error (normalized bias) of radar-raingauge comparisons for the traditional method is 43.9% (-14.1%) and for the optimal method is 27.0% (-10.7%). It's about 17% of improvement for the normalized error when the optimal method is applied.

**Acknowledgments.**

The authors thank Prof. V. N. Bringi of Colorado State University for the usage of their attenuation and differential attenuation correcting program and thank the BMRC for providing the rain gauges and C-POL radar data. This research was partly supported by the grant NSC 95-2111-M-002-018A-P2.

**Reference：**

Austin, P.M., 1987: Relation between measured radar reflectivity and surface rainfall. *Mon. Wea. Rev.*, **115**, 1053-1070.

Aydin, K., H. Direskeneli, and T. A. Seliga, 1987: Dual-polarization radar estimation of rainfall parameters compared with ground-based disdrometer measurements: 29 October 1982, Central Illinois experiment. *IEEE Trans. Geosci. Remote Sens.*, **GE-25**, 834–844.

Bolen, S., V.N. Bringi and V. Chandrasekar, 1998: An optimal area approach to intercomparing polarimetric radar rain-rate algorithms with gauge data. *J. Atmos. Oceanic Technol.*, **15**, 605-623.

Bringi, V.N., T. Keenan and V. Chandrasekar 2001a: Correcting C-Band Radar Reflectivity and Differential Reflectivity Data For Rain Attenuation: A Self Consistent Method with Constraints., *IEEE Trans. Geosci. Remote Sens.* Vol.**39**, No. 9, 1906-1915.

Bringi, V.N., G.H. Huang, V. Chandrasekar and T. Keenan 2001b : An areal rainfall estimator using differential propagation phase: Evaluation using a C-band radar and a dense gauge network in tropics. *J. Atmos. Oceanic Technol.*, **18**, 1810-1818.

Chandrasekar, V., V. N. Bringi, N. Balakrishnan, and D. S. Zrnic, 1990: Error structure of multiparameter radar and surface measurements of rainfall. Part III: Specific differential phase. *J. Atmos. Oceanic Technol.*, **7**, 621–629.

Cressman, G. P., 1959: An operational objective analysis system. *Mon. Wea. Rev.*, **87**, 367-374.

Collier, C.G., 1999: The impact of wind drift on the utility of very high spatial resolution radar data over urban areas. *Phys. Chem. Earth (B)*, **24(8)**, 889-893.

Gunn, K.L.S. and Marshall, J.S., 1955: The effect of wind shear on falling precipitation. *Journal of Meteorology*, **12**, 339-349.

Keenan, T. D., K. Glasson, F. Cummings, T. S. Bird, J. Keeler, and J. Lutz, 1998: The BMRC/NCAR C-band polarimetric (C-POL) radar system. *J. Atmos. Oceanic Technol.*, **15**, 871–886.

Lack, S.A. and N.I. Fox, 2004: Errors in surface rainfall rates retrieved from radar due to wind drift. *Proc. 6th International Symposium on Hydrological Application of Weather Radar*, Melbourne, Australia.

Marshall, J.S., 1953: Precipitation trajectories and patterns. *Journal of Meteorology*, **10**, 25-29.

May, P. T., T. D. Keenan, D. S. Zrnic´, L. D. Carey, and S. A. Rutledge, 1999: Polarimetric radar measurements of tropical rain at a 5-cm wavelength. *J. Appl. Meteor.*, **38**, 750–765.

Zawadzki, I., 1975: On radar-rain gage comparison. *J. Appl. Meteor.*, **14**, 1430-1436.

Zawadzki, I., 1984: Factors affecting the precision of radar measurements of rain. Preprints, 22nd Conf. on Radar Meteorology, Zurich, Switzerland, Amer. Meteor. Soc., 251-256.

Zrnic, D. S., and A. Ryzhkov, 1996: Advantages of rain measurements using specific differential phase. *J. Atmos. Oceanic Technol.*, **13**, 454–464.