Reconstruction of rainfall fields using Microwave Links, Weather Radar, and Rain Gauge: First Results from the China Field Experiments

Bensheng He¹,*, Xichuan Liu¹,*, Yang Xue², b, Taichang Gao¹, c, Peng Zhang³, d and Kun Song¹, e

¹College of Meteorology and Oceanography, National University of Defense Technology, Nanjing, 211101 China
²Department of Xi’an Satellite Control Center, Xi’an Shanxi, 710000 China
³School of PLA Army University of Engineering, Nanjing, 211101 China

*Corresponding author e-mail: liuxc2012@hotmail.com, hbsgfjkdx@outlook.com, xyxhx@foxmail.com, 2009gaotec@gmail.com, radarpeng@126.com, songkun_0521@foxmail.com

Abstract. Inversion of regional rainfall by the attenuation of microwave links has been confirmed a promising method for monitoring large areas of rainfall. To further explore precipitation information from microwave links data, a reconstruct method of rainfall field using microwave links, weather radar and rain gauges is presented in this letter. We utilize mean correction factor method to adjust the rainfall field from radar by microwave links and rain gauges; and validate it by a field experiment using two microwave links, a S-band radar, and 15 rain gauges. The results show that the rainfall field can be improved significantly by joint reconstruction of microwave links, weather radar and rain gauges, and the joint reconstruction in evenly distributed area is better than that in unevenly distributed area. This method supplements an effective approach to reduce the uncertainty of single instrument and improve the rainfall field by using multiple instruments.

Keywords: rainfall field, microwave links, weather radar, reconstruction.

1. Introduction
Quantitative precipitation estimation (QPE) by using weather radar can get regional distribution of rainfall, which plays an important role in meteorological and hydrological fields such as nowcasting of extreme weather, monitoring and warning of heavy rainfall, etc [1, 2]. Currently, the accuracy of QPE depends on the empirical relationship between radar reflectivity Z and rainrate R, many researchers have applied rain gauges or disdrometers to optimize the Z-R relationship continuously [3], however, the rain gauges and disdrometers can only get the spot measurement, and there are extreme complex temporal and spatial variations of the raindrops’ shape, drop size distribution and other factors in natural environment. The uncertainty of QPE by weather radar remains.
The new method for rainrate inversion by microwave links proposed recent years has been confirmed as a feasible and promising approach for monitoring regional rainfall[4, 5], it’s also a supplement to conventional methods such as rain gauges and weather radar[6-10]. Grum [11], Bianchi [12] and Raich [13] carried out joint observation experiments of rain gauges, weather radar and microwave link respectively. Cummings [14] and Liberman [15] used two or more microwave links to correct radar data respectively by using the fusion algorithms based on weighted average and optimum weighted average, and the field measurements validated performance of rainfall field reconstructed by multiple instruments. Nonetheless, there are different spatial representations for different instruments, especially for the random distributions of actual microwave links, the applicability of rainfall field reconstruction using microwave links and weather radar in different region and different rainfall types still need more investigations.

2. Experiment setup

The field experiments are deployed in Nanjing, China, including 2 microwave links, 1 CINRAD-SA weather radar and 15 automatic rain gauges, and their locations are shown in Figure 1. The latitude and longitude of the experimental area is 118.85° N~119.15° N and 32.048° E~32.3° E, the area is 28 × 28 km² divided into 28 × 28 square grids uniformly. It is worth noting that the Yangtze River flows through the target area.

![Fig. 1 Distribution of 2 microwave links, CINRAD-SA weather radar and 14 automatic weather stations in experimental area](image)

The microwave links are operated by Maritime bureau of Jiangsu Province, China. The frequency is 7.7 GHz, and the received signal level (RSL) of microwave links has a resolution of 0.01dB with a 1-min temporal resolution. The squares in Figure 1 represent the transmitters locating at Tianhekou (32.1902 °N, 118.8792 °E) and Yizheng (32.2522 °N, 119.1410 °E), arrow represents receiver locating at Qixia Mountain (32.1590 °N, 118.9625 °E), and the lengths of Link I and Link II are 8.57 km and 19.74 km respectively.

Both the radar and rain gauges are operated by Nanjing Meteorological Bureau, in which the rain gauges have a resolution of 0.1mm with a 5-min temporal resolution, its accuracy is ±0.1mm. The detailed parameters of radar listed in the Table 1. Its maximum detection range is 460 km and elevation range is 0.5° ~ 19.5°, and a total volume scan needs 6 minutes. Noted that although each scan has multiple data points, the echo of radar with higher elevation differ with the rainfall near ground significantly, therefore only the radar data with lowest elevation 0.5° are used to calculate the rainrate, which means that the time resolution of rainrate by weather radar is 6-minute.

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Table 1. Parameters of cinrad-sa weather radar

| Longitude (°E) | Latitude (°N) | Altitude (m) | Wavelength (cm) | Beamwidth (°) | Resolution (m) |
|---------------|---------------|--------------|-----------------|--------------|----------------|
| 118.69        | 32.19         | 138.8        | 10.5            | 0.95         | 1000           |

3. Rainrate inversion by microwave links

The attenuation $A$ (dB/Km) of microwave links in the rainfall with the rainrate $R$ (mm/h) follows the power function generally [8]

$$A = aR^b$$

In which $a$ and $b$ are constants depending on microwave frequency, polarization, atmospheric temperature, rain drop size distribution and etc. The path average rainrate $R$ can be calculated by using above equation when the rain-induced attenuation $A$ is measured. However, the propagation of microwave links can be attenuated by atmospheric gases, dust, water vapor, wet antennas, and other factors. To eliminate the non-rainfall factors, many baseline estimation models have been proposed. Rain attenuation can be obtained by differentiating the signal strength from the calculated baseline attenuation. This paper chooses the method proposed by Ostrometzky [16], which is convenient to calculate and does not require a large amount of prior data for verification. Received signal strength can be considered as total attenuation $A_t$. The minimum value of signal attenuation at the time index $t_i$ is taken as the baseline level, and the difference between $A_t$ and $A_B$ is regarded as the target value $A_r$:

$$A_r(t_i) = A_t(t_i) - A_B$$

Hence the rain-induced attenuation $A_r$ can be calculated by the total attenuations $A_t$ subtracted from the reference attenuation $A_B$.

The power function $A = aR^b$ widely used for rainrate inversion in microwave attenuation, and many researchers have studied the A-R relationship, constant $a$ and $b$ by numerical simulation and field experiments. The model proposed by the International Telecommunication Union in ITU-R Recommendations [17] is widely used in the field of communication links. In this paper, the link is vertically polarized and the frequency is 7.7 GHz. The obtained A-R relationship is $A = 0.00395R^{1.31}$.

Based on the above A-R relationship, the rainrate and rainfall accumulation are inverted from the data on July 14th 2016, as shown in Figure 2. The rain gauges M3556, M3554 are compared with Link I, and M3560, M9229 are compared with Link II. It can be seen that the rainfall reversed by the microwave link is consistent with the rainfall normally recorded by the rain gauge, however, there is still a certain difference in rainfall, resulting in cumulative rainfall deviations.

![Fig. 2](image)

*Fig. 2* Comparison of rainrate and rainfall accumulation by rain gauge and microwave links on 14th July. (a) results of microwave link I and rain gauge M3556 and M3554. (b) results of microwave link II and rain gauge M3560 and M9229

Table 2 lists the comparison of the rainfall accumulation (Racc) and correlation coefficient (CC) rainrate from rain gauges and corresponding microwave links. It can be found that the average CC is 67.99%. Noted that microwave link I has the least deviation with rain gauge M3556. Although M9229 is right on the path of link II, microwave link II has the greatest deviation with rain gauge M9229. The link II is much longer, and it is routed through mountains and rivers. The rain intensity obtained by the
link is the average of the rain intensity on this line. Therefore, the single point measurement of the rain gauge is inevitably subject to errors.

Table 2. Comparison of retrieval from microwave link and measurements of rainfall meter

| Rain Gauge | $R_{acc}$ (mm) | Microwave links | $R_{acc}$ (mm) | CC (%) |
|------------|----------------|-----------------|---------------|--------|
| M3554      | 104.8          |                 | 146.2         | 73.43  |
| M3556      | 121.9          |                 |               | 88.93  |
| M3560      | 184.9          |                 | 218.28        | 63.92  |
| M9229      | 201.4          |                 |               | 45.66  |

4. Rainfall field reconstruction by microwave links, radar, and rain gauge

This paper selects three rainfall events to analyze the reconstruction algorithm. The weather radar is affected by the river echo. First, we remove the clutter from the Yangtze River coverage area and get the first type of rainfall field. Then the rainfall field was reconstructed using 13 rain gauges. The rain intensity data of the rain gauge is $R_{G_{ij}}$, and the rain intensity obtained by the radar data is $R_{R_{ij}}$, then the calibration factors corresponding to each rain gauge point are:

$$F_{R_{ij}} = \frac{R_{G_{ij}}}{R_{R_{ij}}}$$  \hspace{1cm} (3)

The distribution of calibration factors for the entire target area is constructed by interpolation algorithm. The rain intensity data at each point of the radar is multiplied by the corresponding calibration factor to obtain the second type of reconstructed rainfall field.

Finally, the third type of rainfall field is constructed by combining microwave link data. The rain intensity obtained by the microwave link is $R_{L_{ij}}$, and the calibration factor of the point $(i, j)$ is:

$$F_{L_{ij}} = \frac{R_{L_{ij}}}{R_{R_{ij}}}$$  \hspace{1cm} (4)

Areas not covered by the microwave link are processed by interpolation algorithm. The rain intensity at each point of the second field multiplied by the corresponding calibration factor is the final joint reconstructed rainfall field.

This paper chooses Kriging interpolation algorithm[18]. Calibration factor for the prediction area:

$$\hat{F}(x_0) = \sum_{i=1}^{n} \lambda_i F(x_i)$$  \hspace{1cm} (5)

Where $\lambda_i$ represents the weighting factor, which is obtained from the semivariogram function:

$$\gamma(h) = \frac{1}{2} \sum_{i=1}^{n} (F(x_i) - F(x_i + h))^2$$  \hspace{1cm} (6)

$h$ represents the distance of each point. By contrast, the exponential model is applicable to the data in this paper:

$$\gamma(h) = \begin{cases} 
0 & h = 0 \\
c_i + c \left(1 - e^{-h/a} \right) & h > 0 
\end{cases}$$  \hspace{1cm} (7)

$c_0$ represents nugget, $c$ represents sill, and $a$ represents range. They are obtained by fitting the data. According to the Section 2, three devices have different temporal resolutions, therefore we use the rain gauges as reference, the microwave link data were averaged for every 5 minutes, and the radar data were selected according to the rain gauge. Considering the spatial representativeness of weather radar,
only the data at lowest elevation (0.5°) were used to estimate the rainrate by Z-R relation (Z=300R^{1.4} here) in this paper.

Three different rainfall events in Nanjing are observed to testify the above method quantitively. Two rain gauges M3554 (32.1083° N, 118.907° E) and M3415 (32.2794° N, 119.114° E) are selected as verification and do not participate in the reconstruction of the rainfall field. M3415 is near the microwave links, while M3554 is far from microwave links. Firstly, in order to compare the effects, we also use the Kriging interpolation algorithm to obtain the rainfall field of the rain gauge, then calculate the rainfall field from radar before and after correction by rain gauges in each grid, at last reconstruct the rainfall field by joint of microwave links, radar, and rain gauges using above method.

![Rainfall field](image)

Fig. 3 (a), (b), (c), and (d) show the rainfall field from 14:46 to 17:01 on 8th June, 2016. (a) radar estimation, (b) rain gauge interpolation, (c) radar estimation corrected by rain gauges, (d) joint reconstruction of the microwave links, weather radar and rain gauges. (e), (f), (g), and (h) show the rainfall field from 2:16 to 4:32 on 12th June, 2016. (e) radar estimation, (f) rain gauge interpolation, (g) radar estimation corrected by rain gauges, (h) joint reconstruction of the microwave links, weather radar and rain gauges. (i), (j), (k), and (l) show the rainfall field from 8:15 to 10:30 on 14th July, 2016. (i) radar estimation, (j) rain gauge interpolation, (k) radar estimation corrected by rain gauges, (l) joint reconstruction of the microwave links, weather radar and rain gauges.

The results are shown in Figure 3, it can be seen that there is a small regional rainfall on 8th June, a moderate regional rainfall on 12th June, and a widespread rainfall on 14th July, and the performances of rainfall field reconstruction varies with the different rainfall events. Regardless of the type of precipitation, the precipitation center of the rain field obtained by the radar is located in the fixed area. Although the intensity of the radar echo has changed, it is difficult to judge the type of precipitation in the region due to the complex echo distribution of the target area, and the judgment of the precipitation center is not accurate enough (Fig. 3(a),(e) and (i)). The rainfall field of the rain gauge is relatively monotonous. Due to the limited number of meter samples and the sparse distribution (Fig. 3(b), (f) and (j)), there is a significant difference between the rain gauge interpolation and other rain fields. The radar estimations corrected by the rain gauge (Fig. 3(c),(g) and (k))and the joint reconstruction (Fig. 3(d),(h) and (l)) are consistent with each other, except for a few of small deviations in several places. It may be attribute to the adoption of point rainrate from rain gauges and line rainrate from microwave links. For
the light rain event, the rainfall field reconstructed by the joint radar data is less than the original radar data, but the distribution is uneven. The combined reconstruction of the three instruments shows a high spatial resolution and a more reasonable precipitation distribution. Compare with three rainfall events, the reconstructed rainfall fields have the best performance in the widespread rainfall event.

Figure 4 show the variation of rainrate and rainfall accumulation from original radar estimation(RE), radar estimation corrected by rain gauges(RECRG), joint reconstruction by three instruments(JRTI), and selected reference rain gauges (M3554 and M3415). Compared with the original radar estimation, both the radar estimation corrected by rain gauges and the joint reconstruction are improved obviously in all rainfall events, in which the joint reconstruction is much closer to the reference rain gauges. Noted that there are still certain of deviation between joint reconstruction and reference rain gauges, the heavy rainfall tends to be underestimated and the light rainfall tends to be overestimated. The possible reason is that the rainfall field is unevenly distributed, and the weight of heavy rainfall might be weakened and the weight of light rainfall might be strengthened.

Table 3 lists the rainfall accumulation obtained from the radar estimation (RE), radar estimation corrected by rain gauges (RECRG), joint reconstruction using three instruments (JRTI), and reference rain gauges (RRG). For the light rain event, the reconstructed rainfall field has a significant improvement in rainfall calculation. Overall, the combined reconstituted rainfall field is the closest to the rain gauge data. For heavy rain in convective weather, the weather radar calculates a much lower amount of rainfall than the rain gauge. The combined reconstituted rainfall field is not ideal for correcting the rainfall, but it still improves to some extent. The source of this error is largely due to the fact that the weather radar itself in the s-band has a large deviation in precipitation measurement. It can be concluded that compared with the different location of microwave links, uneven distribution of rainfall fields is the main reason for the impact of reconstruction performance.

Table 3. Accumulated rainfall measured before and after correction by rain gauges

| Date | Rain gauge | RE (mm) | RECRG (mm) | JRTI (mm) | RRG (mm) |
|------|------------|---------|------------|-----------|---------|
| 6/08 | M3554      | 5.39    | 2.93       | 3.07      | 3.49    |
|      | M3415      | 5.31    | 3.63       | 3.62      | 3.30    |
| 6/12 | M3554      | 7.27    | 5.70       | 5.39      | 4.32    |
|      | M3415      | 2.79    | 3.80       | 4.27      | 7.2     |
| 7/14 | M3554      | 47.62   | 47.20      | 48.59     | 60.86   |
|      | M3415      | 28.68   | 28.04      | 30.56     | 44.58   |
5. Conclusions
In order to promote the application of microwave links in regional precipitation measurement, this letter presents a method for rainfall field reconstruction using microwave link, weather radar and rain gauges based on correction factor method and Kriging interpolation algorithm; and conduct a field experiment by using 2 microwave links, 1 S-band radar, and 15 rain gauges for the first time in China. The results show that, (1) despite the factors such as complex distribution of rainfall, different distances between microwave links and rain gauges, there are still high correlations between the rainfall inversed by microwave links and measured by rain gauges, (2) joint reconstruction can improve the rainfall field significantly, compared with the selected reference rain gauges, the joint reconstruction of three instruments in evenly distributed rainfall is better than that in unevenly distributed rainfall, (3) the introduction of the path-average rainrate from microwave links in the joint reconstruction of rainfall field can promote the accuracy of regional rainfall significantly, further validate the feasibility and applicability of microwave links in regional rainfall monitoring.

It should be noted that there are only three rainfall events discussed in this letter, several issues still require further research: (i) the reconstruction method should be optimized by using more advanced algorithms; (ii) the effect of topography of microwave links on inversion should be evaluated; (iii) joint reconstruction of multiple rainfall types should be tested systematically in the future.

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