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THE SYNCHRONOUSLY INTEGRATED TECHNIQUE IN REAL TIME RAINFALL ESTIMATION USING RADAR AND RAINGAUGE

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1. INTRODUCTION

There are many integrated techniques studied for radar(R) & raingauge(G). With the help of Krajewsky's issue they can be divided into the climatological and non-climatological by a distinction of using the historical data or the matching data in real time. In this paper, we build up another category of the synchronously integrated or non-synchronously integrated in order to distinguish whether the $Z-R$ conversion and raingauge adjustment are proceeding synchronously or not. Among all $R\,\&\,G$ integrated techniques the climatological methods are mostly combined with the synchronously integrated, while the non-climatological methods are mostly combined with non-synchronously integrated. Such the real-time synchronously integrated are likely seldom to see. Actually, the problem of all $R\,\&\,G$ integrated techniques is the presence of temporal and spatial discrepancies with great resolution differences between the detection of $R\,\&\,G$ (Zawadzki, 1975; Krajewshyet al., 1991; Ciach et al., 1997). One generally considered it is the biggest barrier that makes instantaneously direct correspondence a little possible. Fortunately, our practice has found that the hourly Z(R) accumulations not only have better values of application but also have better correlation which conforming well to Marshall-Palmer's power law. Therefore, the authors recognize that only introducing the concept of quasi-same rain volume sampling, the reasonable and explicit interpretation of the relationship for $R\,\&\,G$ can be acquired.

2. HOURLY INTEGRAL $Z_{OH}-Q_G$ RELATIONSHIP FOR RADAR AND RAINGAUGE

2.1 *Concept of Quasi Same Rain Volume Sampling for* $R\,\&\,G$

The sampling method of DSD(drop size distribution) is called the same rain volume sampling. It is difficultly done as to radar detecting aloft and rain gauge measuring at ground. However, there are some sampling methods having the ability that can make the two separate rain volume samples hold inner physical link and correlative attribution. Thus, the method like this is called Quasi Same Rain Volume Sampling (QSVS).

2.2 *Characters of Temporal and Spatial Discrepancies Sampling*

The $0.5^0 PPI$, as the level mostly relating to the ground rainfall, is served as the radar sampling level. Two characters that can describe the temporal and spatial discrepancies are the preset time τ of radar sampling and the preset distance r along the upwind,

$$\tau = H/\omega, \qquad r = V\cdot\tau \tag{1}$$

in which H is the height from the gauge to the sampling level, ω is the average vertical velocity (relating to the droplet size and rainfall intensity) at which the rain volume is falling from the sampling level down to the gauge, V is the wind velocity of environmental field. H,ω and V can be regarded as the three factors that determine the sampling temporal and spatial discrepancies.

2.3 *Method of QSVS*

In order to gather correlated and corresponding QSV, $R\,\&\,G$ must be sampled by three specific methods: tilt asynchronous, vertical asynchronous and vertical synchronous, and in two special forms: instantaneous and integral form, from which five kinds of methods for QSVS are constructed as summarized in Table 1. Their characteristics are explained in the following two categories.

Table 1 The five methods of QSVS

Correspondence mode	Exact QSVS correspondence		Approximate QSVS correspondence
	Tilt Asynchronous Sampling (wind)	Vertical Asynchronous Sampling(calm)	TIVS
Instant correspondence	$Z(x_G-r,H,t-\tau) \rightarrow R(x_G,0,t)$ (2)	$Z(x_G,H,t-\tau) \rightarrow R(x_G,0,t)$ (4)	
Integral correspondence T=1hr.	$\int_0^T Z(x_G-r,H,t-\tau)dt \rightarrow \int_0^T R(x_G,0,t)$ (3)	$\int_0^T Z(x_G,H,t-\tau)dt \rightarrow \int_0^T R(x_G,0,t)dt$ (5)	$\int_0^T Z(x_G,H,t)dt \sim \int_0^T R(x_G,0,t)dt$ (6)

1) Accurate QSVS— temporal and spatial coordinate sampling

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The method to accurately eliminate the temporal and spatial discrepancy is called temporal and spatial coordinate sampling, in which tilt asynchronous sampling has to be used. The “tilt” means that when wind exist, the original position at the radar sampling level must be move forward r distance along the upwind vertically above the correspondent gauge. The “ asynchronous ” means that the radar must sample early in τ time. Instantaneous tilt asynchronous is presented in the equation (2) in table 1.

2) Approximate QSVS—Time Integral Vertical Synchronous Sampling (TIVS)

Actually, the temporal and spatial discrepancies are not taken into account in the vertical synchronous sampling, so its instantaneous correspondence is not established. However, it is important that the Time Integral Vertical Synchronous Sampling (TIVS) in general contains so comparatively high QSV elements as to become approximate QSVS. Because of its easy operation TIVS is significantly practical and is studied first in this paper.

2.4 *Characteristics and Availability of TIVS*

When there is no wind or the wind is gentle the availability of TIVS is good. When the wind direction doesn’t change with height, especially when the wind vertical shear is relatively smaller, the availability of TIVS is relatively good. But when the wind direction varies with the space, especially when the angle is relatively larger and the precipitation fields are more non-uniformly distributed, the availability of TIVS becomes worse. Additionally, the availability is generally influenced by the three factors of the temporal and spatial discrepancies. When the distance away from the radar is shorter, the wind velocity is smaller and the rain intensity is larger, the availability becomes better and vice versa. The availability of TIVS is relatively good in general situations, which conforms to the observational results revealed in Fig.1.

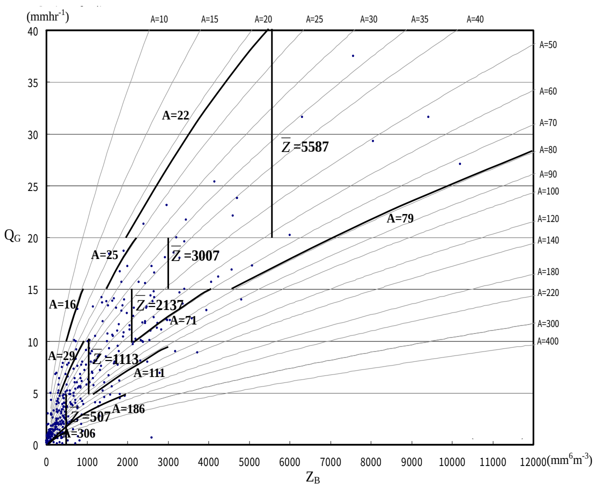

Fig. 1. (Z_B,Q_G)scatter plot with A_B contours as background, quality control extents of A_B at Q_G intervals are denoted by thick lines.

2.5 *RASIM Method*

Based on concept of quasi same rain volume sampling for R & G , the power law relationship between the hourly accumulations of radar (Z_{OH}) and gauge (Q_G) can be established. It’s called RASIM (RAdar-gauge Synchronously Integrated Method), that the synchronously integrated technique in real time for rainfall estimation using $Z_{OH} - Q_G$ relationship of hourly radar integral reflectivity and ground rainfall accumulation. After introducing a fixed component (Smith, 1997), this method is quite convenient and easily implemented in practical operation.

a. Instantaneous $Z - R_G$ relationship

According to the accurate sampling method coordinating in time and space, there is a full reason to transform the expressions $Z = A \cdot R^b$ into the corresponding instantaneous power law relationship:

$$Z(x_G - r, H, t - \tau) = A_B R_G^b(x_G, 0, t) \qquad (7)$$

Among the equation(7), x_G denotes the site of gauge, r denotes the difference of radar and gauge sampling horizontal position, H denotes the high of radar sampling, t denotes the time of radar and gauge sampling, τ denotes the difference of radar and gauge sampling time. The coefficient A_B differs from A in the equation $Z = A \cdot R^b$. It performs two physical meanings of expressing the change of the falling rain volume from the sampling level of radar to the gauge, and adjusting the resolution discrepancies between radar and gauge detecting. Hence, $Z - R$ conversion and the gauge adjustment are combined in the single equation (7), so this is a very important characteristic.

b. Integral $Z_B - Q_G$ relationship

1) $Z_B - Q_G$ relationship of single station

Deriving R_G from the equation (7) and using the principle of tilt synchronization sampling, and introducing the fixed component b_f and integrating with time, then:

$$Q_G = \int_0^T R_G(x_G, 0, t)dt = A_B^{-\frac{1}{b_f}} \int_0^T Z^{\frac{1}{b_f}}(x_G - r, H, t - \tau)dt \qquad (8)$$

In equation (8), Q_G is the rainfall accumulation of gauge while A_B is the average value in the period T. Actually, if the tilt asynchronous sampling is changed by TIVS, the equation (8) also approximately exists, but the equal sign is still be used, and then:

$$Q_G = \int_0^T R_G(x_G, 0, t)dt = A_B^{-\frac{1}{b_f}} \int_0^T Z^{\frac{1}{b_f}}(x_G, H, t)dt \qquad (9)$$

Omitting the integral symbols in equation (9) and introducing the symbols of Z_B meaning the accumulations of Z, then equation (9) with integral form is changed to the relationship of accumulations between radar reflectivity and gauge measure, see the formula (10) as follow:

$$Q_G = A_B^{-\frac{1}{b_f}} Z_B^{\frac{1}{b_f}} \qquad (10)$$
$$Z_B = A_B Q_G^{b_f}$$
$$Z_B = \left[\int_0^T Z^{\frac{1}{b_f}} dt \right]^{b_f}$$

2) Regional $Z_{BS} - Q_{GS}$ relationship

In region S which including some stations, then the equation (11) is derived from formula (10) by using integral form of $Z_B - Q_G$ relationship of single station:

$$\iint_S Q_G ds = \iint_S A_B^{-\frac{1}{b_f}} Z_B^{\frac{1}{b_f}} ds \qquad (11)$$

After changing equation (11) to summing form of all single station in the region S, then:

$$Q_{GS} = A_{BS}^{-\frac{1}{b_f}} Z_{BS}^{\frac{1}{b_f}} \qquad (12)$$
$$Z_{BS} = \left[\sum_{i=1}^{N} Z_{Bi}^{\frac{1}{b_f}} \right]^{b_f}$$
$$A_{BS} = \left[\frac{\sum_{i=1}^{N} Z_{Bi}^{\frac{1}{b_f}}}{\sum_{i=1}^{N} Q_{Gi}} \right]^{b_f}$$

In the formula (12), A_{BS} is the representative coefficient and N is the number of gauge stations in the region S; Z_{Bi} and Q_{Gi} represent accumulations of radar reflectivity and gauge measure of single station respectively.

3. OPERATIONAL APPLICATION AND EVALUATION OF RASIM

3.1 *Quality Control of Data.*

The property of quasi-same samples of (Z_B, Q_G) sometimes contains relatively large random errors resulting from many factors such as: droplet diameter, wind field, the vertical current and the micro physical process of rain volume. Therefore the quality control to data must be conducted in TIVS sampling. In the scatter plot of (A_B, Q_G) as Fig.2, the value of A_B changes from high divergence to rapid convergence with the increase of Q_G. Thus, the first quality control step is that the observation data of radar and gauge are deleted when $Q_G < 1.0$ mm. What is emphasized is that the clutter of radar echo must be eliminated before data quality control (Wang, 2006).

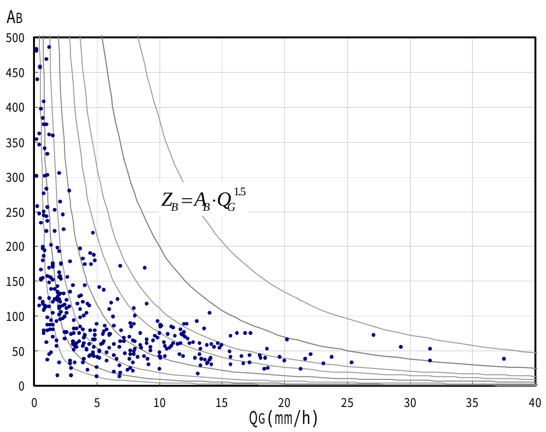

Fig. 2. (Q_G, A_B) **scatter plot with Z_B contours as background.**

3.2 *Rainfall Estimation.*

The hourly radar rainfall estimation is calculated by using the equation (13) at each pixel (x, y) in radar domain.

$$Q_{RB}(x,y) = A_{BS}^{-\frac{1}{b_f}} \cdot Z_B^{\frac{1}{b_f}}(x,y) \qquad (13)$$
$$= \sum_{i=1}^{N} Q_{Gi} \cdot Z_B^{\frac{1}{b_f}}(x,y) \Big/ \sum_{i=1}^{N} Z_{Bi}^{\frac{1}{b_f}}$$

3.3 *Evaluation of Radar Rainfall Estimation*

The evaluation criterions are E (ratio of the radar estimation and gauge measure) and FAE (fractional absolution error, simplified as F). Their expressions are as follows (Klazura, 1995):

1) Evaluation at region

$$E(S) = \frac{1}{M} \sum_{t=1}^{M} \left(\frac{\sum_{i=1}^{N} Q_{Ri,t}}{\sum_{i=1}^{N} Q_{Gi,t}} \right) \qquad (14)$$

$$F(S) = \frac{1}{M} \sum_{t=1}^{M} \left(\left| \sum_{i=1}^{N} Q_{Ri,t} - \sum_{i=1}^{N} Q_{Gi,t} \right| \Big/ \sum_{i=1}^{N} Q_{Gi,t} \right)$$

in which $E(S)$ and $F(S)$ are criterions of region, M is the number of hours in a rain event , N is the number of stations with rainfall at the region, $Q_{Ri,t}$ and $Q_{Gi,t}$ are the hourly accumulations respectively made by radar estimation and gauge measure at the i[th] gauge station and t[th] hour.

2) Evaluation at point

The average $E(S)$ and $F(S)$ are used as point evaluation criterion in whole rain event and region for each station:

$$E(P) = \frac{1}{N} \sum_{i=1}^{N} \left(\sum_{t=1}^{M} Q_{Ri,t} \Big/ \sum_{t=1}^{M} Q_{Gi,t} \right) \qquad (15)$$

$$F(P) = \frac{1}{N} \sum_{i=1}^{N} \left(\left| \sum_{t=1}^{M} Q_{Ri,t} - \sum_{t=1}^{M} Q_{Gi,t} \right| \Big/ \sum_{t=1}^{M} Q_{Gi,t} \right)$$

3.4 *Primary Results of Tests*

Two typical cases (20:00UTC17June2004—0700UTC 18 June and 01:00UTC 18 July 2004 - 0000UTC 19 July) were chosen in this paper as test. The tests were divided by two situations. Firstly, the rain gauges (41) were not grouped. Secondly they were grouped into two groups-A(20) and

B(21). The rain gauges in each group are uniformly distributed in radar domain as possible. One group as estimating rainfall while another as evaluation test. The tests are hourly proceeding as being put in operation in real time. Consciously, suppose $b_f = 1.5$ in order to verity the sensitive to exponent impacting on rainfall accumulation calculation.

1) Whether or not using A_{BS}, there is a significant improvement comparing with the estimate with $(300,1.4)$ relationship. Obviously from Fig.3, the $\sum Q_R(300,1.4)$

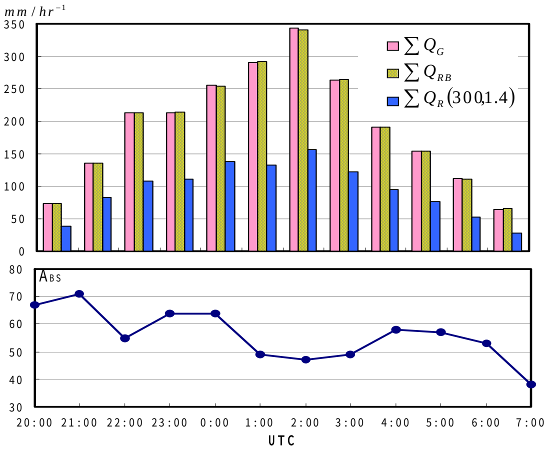

Fig. 3. Rainfall accumulation of rain gauges in Wuhan Radar effect area and hourly evolution curves of A_{BS}(case 1)

underestimate seriously just reaching one half of $\sum Q_G$. The $Z = 300R^{1.4}$ proposed by woolly (Doviak et al. 1993) in 1975 later adopted by NEXRAD is basically adapted in average in USA reported by Uijlenhote et al. (2001), but it have not got good applications effects in Changjiang River of China in Summer. Actually, the coefficient of $Z_B - Q_G$ relationship is changed hourly as shown in fig.3.

2) Comparison of point evaluation by single and dual quality control. From table 2 see under the condition of

Table 2 Test statistics of evaluation for estimated rainfall accumulation under single and dual quality control

Quality Control	Case 1				Case 2			
	Region eval.		Point eval.		Region eval.		Point eval.	
	E(S)	F(S)	E(P)	F(P)	E(S)	F(S)	E(P)	F(P)
Single	1.00	0.00	1.05	0.20	1.00	0.00	1.08	0.28
Dual	1.00	0.00	1.02	0.16	1.00	0.00	1.06	0.25

single data quality control the $F(P)$ are 0.20 (Case1), and 0.28 (Case2). But the $F(P)$ in Case1(2) can again reduce 4% after using dual quality control. Hence, it is very necessary to use the dual quality control to reduce $F(P)$.

3) Comparison of convective and strait form rainfall. From Table 2 see, the $F(P)$ in Case 2 is larger about 8% than in Case 1. So the RASIM also has the weakness when estimating convective rain.

4) Comparison of classes for distance segment and rain intensity. Statistic table is omitted. Primary results can be briefly expressed:

In comparison of 4 distance segments (interval 50km), there is a little overestimate in near and far distance segments, radar estimation is equivalent-estimate or a little underestimate than gauge measurement in middle segment.

From view of statistics for 6 rainfall intervals there are some features as more overestimate when small rain, underestimate when heavy rain and equivalent-estimate when medium rain. The results of above are caused from that only one representative $A_{BS} - Q_G$ relationship is adopted in whole radar coverage in each hour.

5) Comparison of raingauges grouping. The region evaluation can not maintain optimal effect when the raingauges are grouped. When exchanging the task between group A and B, the $E(S)$ of A_{BS} for both groups are 0.93 and 1.08 respectively, $F(S)$ are 0.07 and 0.08. The point evaluation $F(P)$ for both groups is within 0.21 and 0.18 in average. So it is explained that the result using RASIM even in non grouping for raingauges is basically confident.

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