SPATIAL RAINFALL RATE ESTIMATION THROUGH COMBINED USE OF RADAR REFLECTIVITY AND RAINGAUGE DATA

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***Abstract*—In this work we propose a procedure for the estimation of the spatial distribution of the rainfall rate in the observation time *T* over an area covered by a meteorological radar and a raingauge network. *T* can be the whole duration of a rainfall phenomenon or a part of it. The procedure is applied to a data set composed by PPI scans of absolute reflectivity gathered by a weather radar and by point rainfall measurement as provided by a raingauge network over the area monitored by the radar. The procedure was applied and tested on a experimental dataset related to a one-day precipitation phenomenon observed in Tuscany (Italy) on 29 October 1999, along the Arno river basin. The performance of the proposed procedure has been evaluated assuming a subset of the raingauge network as "true" rainfall rate reference.**

Keywords; Rain radar, raingauge, rainfall rate, data fusion.

I. Introduction

It is recognized that rainfall rate estimate based on radar measurements is affected by an high degree of uncertainty due to several sources: space-time variability of drop size distribution (from one rainfall event to another and within the same event), variations in space and time of reflectivity with height, radar signal attenuation due to propagation in the precipitation rainfall, etc. [1]. Moreover, the most common validation way to asses the reliability of the rainfall radar estimates is the comparison with data provided by an ensemble of raingauges placed in the radar coverage area [1]-[7].

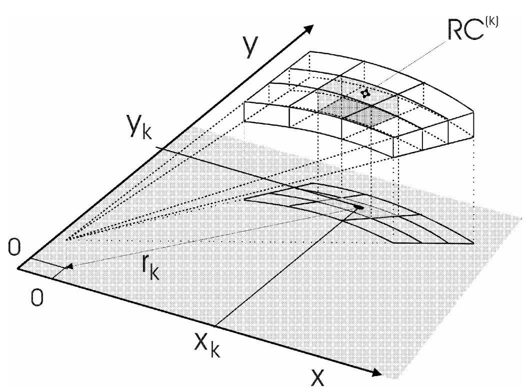

Fig. 1 – spatial disposition of N_z=9 adjacent radar cells considering the location (x_k , y_k) of the k[th] raingauge.

In this work we describe a raingauge-radar processing method for the determination of the spatial distribution of the rainfall rate $R_T(x,y)$ over an area covered by a meteorological radar and a raingauge network during the observation time *T*. Such proposed method processes the instantaneous absolute reflectivity ***Z*** as provided by the radar and the estimates of rainfall ***R*** as provided by raingauges, both collected during a given observation time *T*, in order to compute the rainfall rate $R_T(x,y)$ as:

$$\log(R_T(x,y)) = A_T(x,y) + B_T(x,y)\log(Z_T(x,y)),$$

where $Z_T(x,y)$ is an average function of the instantaneous horizontal reflectivity maps (PPI scans) gathered during the observation time *T*, while $A_T(x,y)$ and $B_T(x,y)$ are coefficients that are determined by means of *ad hoc* correlation functions between space-time "average" values of raingauge data and absolute reflectivity data.

II. Procedure for computing the Z-R relationship

In order to introduce the proposed method, some parameters must be preliminarly defined, relative to the radar and raingauge data sets: $\mathrm{R}_i^{(k)}$ is the i^{th} time rainfall sample of the k^{th}

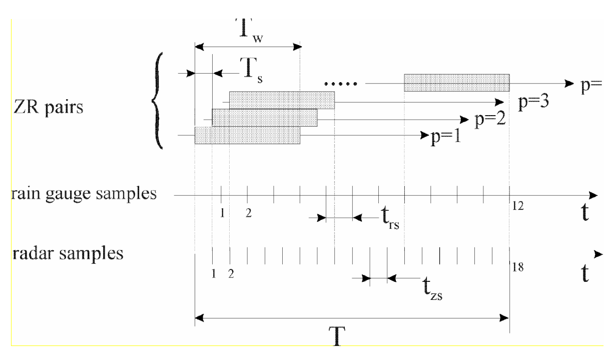

Fig. 2 – Example of the relative position of the time parameters with respect to the observation time *T* (t_{rs} raingauge sampling time, t_{zs} radar sampling time). In the case of the picture we have $3t_{zs}=2t_{rs}$, n_{zs}=18, n_{rs}=12 $T_w=6t_{zs}$, n_{rw}=4, n_{zw}=6 and np=13.

raingauge and $Z_{m,i}^{(k)}$ is the i^{th} time sample of radar reflectivity of the m^{th} adjacent spatial radar cell around the k^{th} raingauge location (see Fig.1). Fig, 2 shows a time graph with the time parameters that are defined and used throughout this work. T_w is referred to as the processing time: it must be smaller than the observation time T and greater than twice both t_{rs} and t_{zs}. In this way, T_w includes at least two samples of both $R_i^{(k)}$ and $Z_{m,i}^{(k)}$ for each raingauge location. All the $Z_{m,i}^{(k)}$ are gathered with the same radar elevation angle (PPI scans).

Let us define $ZS_j^{(k)}$ as the spatial arithmetical average of $Z_{m,i}^{(k)}$ with respect to the index m and $ZW_p^{(k)}$ as the moving average of $ZS_j^{(k)}$ with respect to the index j. Finally, let us define $RW_p^{(k)}$ as the moving average of $R_i^{(k)}$ with respect to the index i. In this way, in correspondence of each raingauge k, we have np pairs of Z-R values within the observation time T that are related to the (moving) time window T_w.

Fig 3 shows some examples of $(ZW_p^{(k)}, RW_p^{(k)})$ pairs computation using a set of data acquired in Tuscany in autumn 1999; two different raingauge locations are considered. Notice that we get different results with different raingauges and with different T_w. These differences indicate that the rainfall phenomenon was not stationary and not homogeneous.

If a linear regression method is applied to the np pairs of ZR we obtain two coefficients of the regression line, $a_0^{(k)}$ and $b_0^{(k)}$, for each raingauge location. These coefficients are assigned to the functions A_T and B_T in the raingauge locations (x_k,y_k). A_T and B_T in any other generic point (x,y) are computed

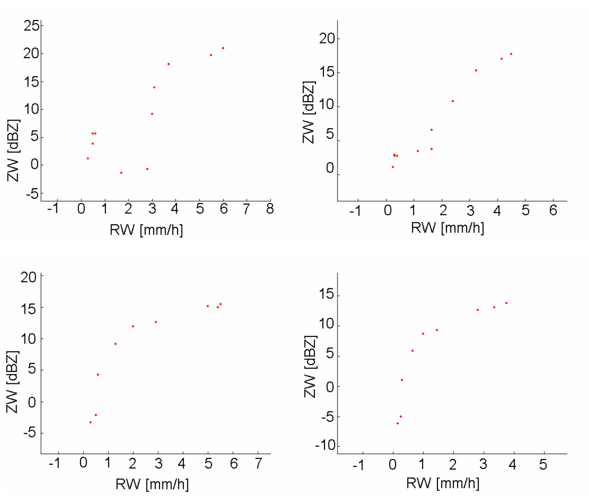

Fig. 3 – Z-R pairs computed on raingauge and radar data acquired during a rainfall phenomenon in Tuscany (Italy) on 21 October 1999 from 11:40:00 to 22:20:00 local time; data processing parameters: t_{zs}=10 min, t_{rs}=15 min, N_z=9, T=640 min. (Top) radar-raingauge distance: 42.675 km, (down) radar-raingauge distance: 16.764 km. (left) T_w=120 min, (right) T_w=240 min.

by a space-time 2D bilinear interpolation on the ensembles $A_T(x_k,y_k)$ and $B_T(x_k,y_k)$, respectively. $Z_T(x,y)$ is simply the arithmetical mean of $Z_{j,m}(x,y)$ with respect to the indexes j and m.

III. Computing the A_T and B_T functions

The procedure described allows to estimate the rainfall rate on a the time interval basis T once defined the extension of the precipitation volume to be correlated to the raingauges, through the number of adjacent radar resolution cells, and the processing time T_w to obtain a number of pairs Z-R through which the coefficients $a_0^{(k)}$ and $b_0^{(k)}$ are computed in each raingauge location.

The method does not make use of *a priori* parameters and the relationship between reflectivity and rainfall rate is variable in both time and space. This approach allows to account for the evolution of the precipitation phenomenon. In fact, the simultaneous and time-continuous use of raingauge and radar reflectivity data simultaneously allows to modify in real time the relationship between the rainfall rate and the radar observation.

As said, the coefficients $A_T(x_k,y_k)$ and $B_T(x_k,y_k)$ are determined through a regression methods applied to the np pairs $(ZW_p^{(k)}, RW_p^{(k)})$. Each pair can be given a score in terms of reliability and uncertainty in order to quantify the level of the correlation between radar reflectivity and raingauge rainfall rate. We assume that the less stationary and homogeneous the precipitation phenomenon, the lower the correlation between radar reflectivity and raingauge rainfall estimates. Consequently, we assume that if the precipitation phenomenon is stationary and homogeneous during the processing time T_W it is very likely that the values of $ZW_p^{(k)}$ and $RW_p^{(k)}$ are highly correlated.

We quantified the level of reliability and uncertainty of the pair $(ZW_p^{(k)}, RW_p^{(k)})$ based on the level of the space time variability of the ensemble $Z_{m,i}^{(k)}$ and $R_i^{(k)}$. For this purpose, we defined 3 parameters of reliability: $RRt_p^{(k)}$, $RZt_p^{(k)}$ and $RZs_p^{(k)}$.

The first two are the root mean square values of $R_i^{(k)}$ and $ZS_j^{(k)}$ with respect to the index i and j, respectively, while $RZs_p^{(k)}$ is an “adapted” spatial root mean square value of $Z_{m,j}^{(k)}$ with respect to the indexes m and j.

The ideal condition of stationary phenomenon during the processing time T_w in (x_k,y_k) is $RRt_p^{(k)}=0$ and $RZt_p^{(k)}=0$, while the ideal condition of homogeneity is $RZs_p^{(k)}=0$.

Depending on the regression method used for the computation of $a_0^{(k)}$ and $b_0^{(k)}$, different global uncertainty indexes on both the $ZW_p^{(k)}$ and $RW_p^{(k)}$ dataset can be defined as functions of the 3 parameters of reliability.

To relate the values of $\mathrm{ZW}_p^{(k)}$ and $\mathrm{RW}_p^{(k)}$ 3 approaches can be followed. In the first, both are ideally supposed to be not affected by uncertainty for all the *np* pairs, namely they are considered equally reliable and no uncertainty indexes are needed, and therefore a standard linear regression method is sufficient. In the second approach, $\mathrm{RW}_p^{(k)}$ and $\mathrm{ZW}_p^{(k)}$ are assumed without and with uncertainty, respectively, for all the *np* pairs; then the uncertainty index $\sigma_{Zp}^{(k)} = f_z\left(\mathrm{RZt}_p^{(k)}, \mathrm{RZs}_p^{(k)}\right)$ is defined to account for the conditions of non homogeneity and non stationariety on the radar dataset. In this case, a standard least square method is used.

In the last approach, both $\mathrm{RW}_p^{(k)}$ and $\mathrm{ZW}_p^{(k)}$ are assumed with uncertainty for all the *np* pairs, $\sigma_{Zp}^{(k)} = f_z\left(\mathrm{RZt}_p^{(k)}, \mathrm{RZs}_p^{(k)}\right)$ and $\sigma_{Rp}^{(k)} = f_R\left(\mathrm{RRt}_p^{(k)}\right)$ are defined in order to account for the conditions of non homogeneity and non stationarity on the $\mathrm{ZW}_p^{(k)}$ dataset and for the non stationarity on the $\mathrm{RW}_p^{(k)}$ dataset. In this case, the effective variance method [8] is used.

Summarizing, for the computation of $a_0^{(k)}$ and $b_0^{(k)}$:

1. the standard linear regression method is used if the phenomenon can be considered stationary and homogeneous;
2. the least square method is used if the phenomenon can be considered stationary;
3. the effective variance method is used in all other cases

IV. PERFORMANCE ANALYSIS

The performance analysis of the proposed method was made on the whole radar and raingauge dataset related to the rainfall phenomenon occurred over Tuscany (Italy) on 21 October 1999 from 11:40:00 to 22:20:00 local time, observed by the dual polarization radar POLAR 55C in the site of Montagnana (Firenze). Fig. 5 shows the spatial disposition of the 22 raingauges used in this work assuming the radar located in (0,0).

We considered several combinations of time parameters (1 to 20 h step 20 min for T, 10 min to 3 h step 10 min for T_w, 5 to 20 min step 5 min for T_s) and all the three regression computation methods discussed in the previous section. For each combination, we selected 18 raingauges for the calibration procedure and 4 raingauges for validation. In order for the test

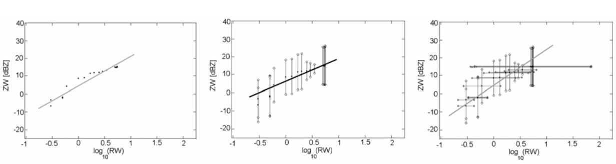

Fig. 4 - Example of Z-R regression computation: (left) linear regression, (center) least square, (right) effective method

to be statistically significant, all possible combinations of calibration and validation raingauge ensembles, among the

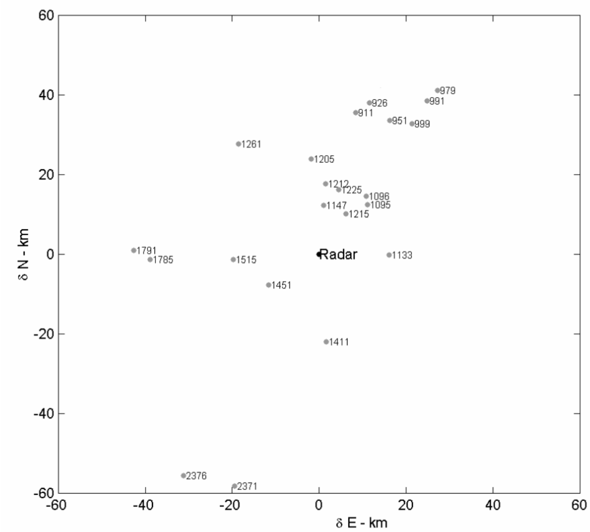

Fig. 5 – Geographical disposition of the 22 raingauges with respect to the radar position.

available 22 raingauges, were considered. Therefore, 385 different combinations of validation cases were obtained for each set of time parameters.

The value of the coefficients A_T and B_T corresponding to a validation raingauge site are computed considering two different 2D interpolation methods: the first is a standard bilinear interpolation on the A_T and B_T of the 4 calibration raingauges much closer to that of validation, the second is still based on a spatial bilinear interpolation, but it accounts also for a time correlation index between the radar sequences over the locations of the validation and the calibration raingauges. The complete results are summarized in Fig. 6 in terms of percentage error of the rainfall rate estimation over the validation raingauge site, versus the cumulated frequencies. Notice in particular that:

a) the effective variance method to find the $a_0^{(k)}$, $b_0^{(k)}$ coefficients gives the best results independently of the 2D interpolation method used;

b) of the two 2D interpolation methods, that based on the time correlation index is slightly better;

c) when using the effective variance method, the estimation error of the rain fall rate is always lower than 60%, independently of the set of time parameters chosen for the processing procedure and of the ensembles of validation/calibration raingauges.

The results shown in Fig. 6 were compared to those obtained using a constant value of A_T and B_T in the whole 2D area. This constant value was chosen basing on standard Z-R relationships that are frequently found in the literature [4]. Here we use the following 4 parameter pairs:

1. A_T=-1.86, B_T=0.77,
2. A_T=-1.82, B_T=0.77,
3. A_T=-1.60, B_T=0.60,

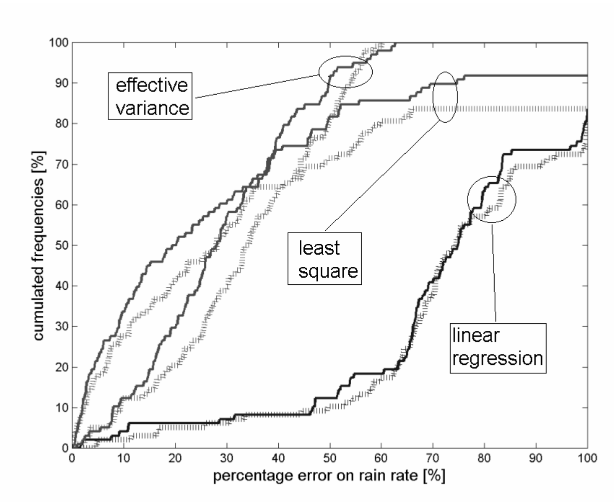

Fig. 6 – Estimation error of the rainfall rate considering all the possible validation ensembles composed by 4 raingauges and calibration ensemble composed by 18 raingauges.

4. A_T=-1.44, B_T=0.62,

assuming that R is expressed in [mm h^{-1}] and Z in [mm^6 m^{-3}].

Using all the possible combinations of 4 raingauges as validation ensembles we obtained the 4 graphs reported in Fig. 7. Notice that the estimation error is always dramatically high, therefore a constant value for A_T and B_T for the whole monitored area does not offer acceptable results.

V. Conclusion

The procedure proposed in this work allows the estimation of the rainfall rate over an area covered by a meteorological radar and a raingauge network. Such procedure is based on the local space-time calibration of the radar horizontal reflectivity through the raingauge data. The procedure has been tested on an a radar-raingauge data set obtained during a precipitation event occurred in Tuscany (Italy) in 1999. The results show that the 2D distribution of the rainfall rate can be estimated always with error lower than 60 %. Many other tests with different data set corresponding to different precipitation phenomena must be done in order to quantify the general performance. Moreover, such test will allow the refinement and the tuning of all the parameters involved in the data processing procedure.

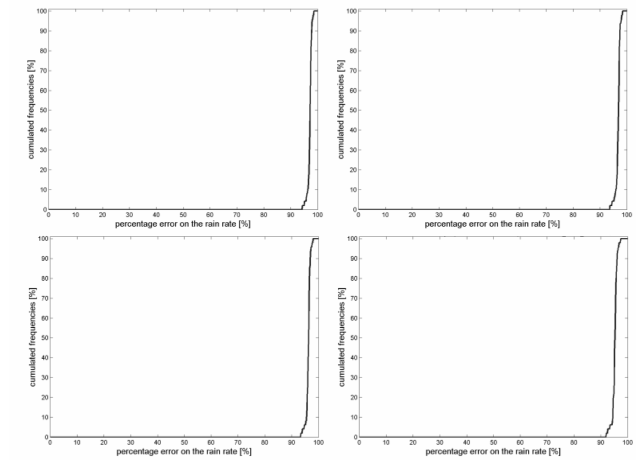

Fig. 7 – Estimation error of the rainfall rate considering all the possible validation ensembles composed by 4 raingauges. Rainfall estimation is made considering constant values of A_T and B_T. top-right: A_T=-1.86, B_T=0.77; top-left: A_T=-1.82, B_T=0.77; bottom-right: A_T=-1.60,B_T=0.60; bottom-left: A_T=-1.44, B_T=0.62

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