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An implementation of Kalman filter in north-western Italy for radar calibration using 3-hourly gauges measurements and polarimetric c-band radar estimates

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Abstract. North-western Italy is surveyed, with the primary objective of providing accurate rainfall monitoring, by about 350 real-time rain gauges – about 1 station every 100 km^2 – and a multiparametric C-band weather radar. The region monitored, extending over North-Western Italy, Southern Switzerland and South-Western France is characterized by complex orography and dense river network. Radar systems have Doppler and polarization capabilities, allowing measurement of four parameters: Z_H, Z_{DR}, V, σV. Rainfall estimation from radar are affected by several sources of error, due to instrumental and environmental conditions. The aim of this work is the evaluation of a Kalman filter's implementation for real-time radar calibration, based on 3 hourly dense network gauges and radar data.

1 Introduction

ARPA Piemonte manages a large meteorological monitoring system, in partcular a well distributed net of raingauges and two multiparametric C-band radars having the main objective of providing accurate rainfall monitoring for hydrologic risk management.

Rainfall estimation by radar data, affected by various types of errors awardable to complex orography and variability of beam propagation conditions, are usually derived by data corrected using a clutter suppression algorithm and a correction for vertical profile of reflectivity, and then are calibrated with raingauges using a factor of correction, the assessment factor (AF), obtained comparing radar and raingauges data. This work is addressed to evaluate the results obtained calibrating real-time radar rain amounts with factors of correction simulated by a Kalman filter implementing algorithm, in view of a future operational application of Kalman filtered AF.

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For testing the algorithm's performance has been considered a rainfall stratiform event occurred on 24 November 2002, using data measured by Bric della Croce radar, located above the Turin hill.

2 Instrumentation

2.1 Radar system

Bric della Croce radar is a C-band polarimetric system that measures Z_H, Z_{DR}, V, σV. Its antenna diameter is 4.2 m, giving a 1.0 deg beam width, with sidelobe level below −28 dB.

The operational schedule consists of two volume scans, repeated at intervals of 10 min: a short range volume scan (125 Km), with a set of 11 elevations, and a long range one (250 Km), with 4 elevations. The short one is characterized by a PRF of 1100 Hz and the number of integrated short pulses (0.5 μs) is 120 (H-H-V transmitting mode), the long one has PRF of 500 Hz, and integrates 33 long pulses (2 μs). The rainfall estimation algorithm is currently applied only on the short range volume scan, because of the higher accuracy of measurements.

2.2 Rain-gauges network

The rain-gauges of the ARPA Piemonte monitoring network counts about 350 raingauges. They are tipping-bucket type, with a temporal resolution of 10 min, and send data to the Meteorological centre in Torino via a radio link. Figure 1 shows the ground stations distribution over the regional territory.

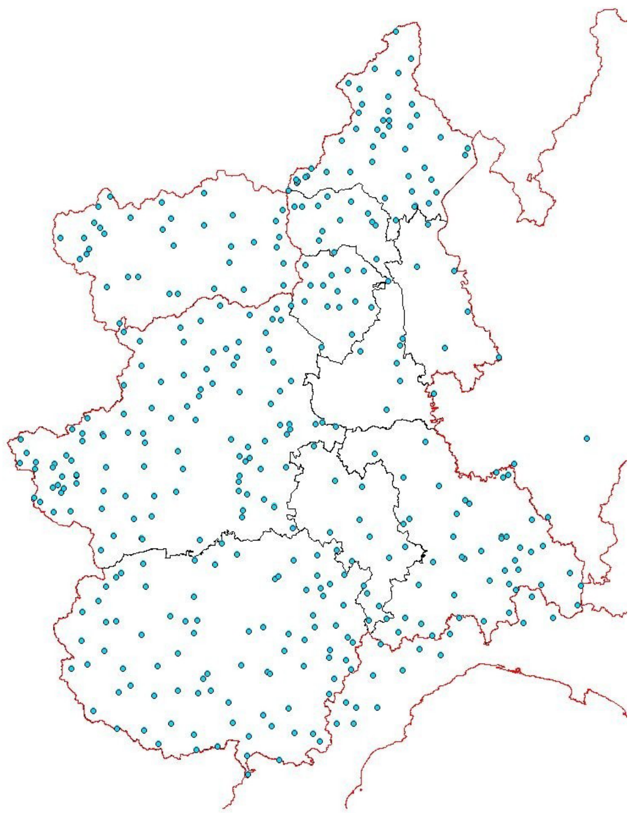

Fig. 1. Map of the ARPA Piemonte ground stations network.

3 Rainfall estimation

In order to give a reliable estimation of rainfall at ground, a sequence of elaborations of radar data is made.

Clutter suppression

For the Bric della Croce radar an algorithm based on three different tests – Doppler test, Statistical clutter, Variance of Z_{DR} – is operationally used to flag clutter contaminated data during the post-processing of polar volumes (Cremonini R. and Bechini R., 2003).

Radar rain rate estimation

A 2-D reflectivity polar map of the lowest visible radar cell is derived from the clutter flagged volume, on the basis of DEM with 500 m resolution. Due to the presence of complex orography the first visible radar cell is often far from ground, so a correction for mean Vertical Profile of Reflectivity (VPR) is necessary. The mean VPR is calculated averaging profiles up to 50 Km from radar over the last hour, in order to prevent from strong underestimation due to measurements above the freezing level, and overestimation for measurements within the melting layer. The mean VPR used is distance-dependant to allow for the beam broadening, according to the Gaussian shape of antenna diagram. After VPR correction, a Marshall-Palmer law, with coefficients A=300 and B=1.5 (Joss and Waldvogel, 1970), and a median filter on the polar map are applied, in order to obtain the surface rainfall intensity in mm/h. The total rainfall amount over a certain period is derived integrating the instantaneous rainfall intensities, assumed constant during the 10 minutes time between successive radar scans.

Cumulated rainfall fields: correction by the Assessment Factor

The resulting radar map of cumulated precipitation is eventually corrected for the Assessment Factor (AF) between radar and gauges. The AF is the ratio between the precipitation measured by the rain-gauge and the corresponding radar estimate, over a certain period of time:

$$AF = 10 \cdot \log_{10}\left({}^{G}\!/_{R}\right) \tag{1}$$

where G and R are respectively the rain-gauge and radar cumulated rainfall.

The corrected radar field of precipitation is given by the product of the original radar map and the AF interpolated field:

$$R_{corr} = R_{radar} \cdot 10^{AF_{interp}/10}, \tag{2}$$

where R_{corr} and R_{radar} are respectively the corrected and the original radar rainfall field, while AF_{interp} is the interpolated field of the AF.

4 Kalman filter

The Kalman filter is a set of mathematical equations that provides an efficient computational (recursive) mean to estimate the state of a process, in a way that minimizes the mean of the squared error. The filter is very powerful in several aspects: it supports estimations of past, present, and even future states, and it can do so even when the precise nature of the modelled system is unknown.

Our objective is to estimate an AF for every raingauge of Piedmont net, during the event occurred on 24/11/2002. The AF dynamic is described by this equation:

$$AF_{\exp}(t + \tau) = AF(t) + w_t \tag{3}$$

where $AF_{\exp}(t + \tau)$ is called a priori (expected) estimate, t and t + τ are two consective instants, the state variable AF is considered consant, and w_t is the error which must have normal probability distribution with mean = 0 and variance = Q. For every raingage Q is estimated using this formula:

$$Q = \frac{\sum_{i=1}^{n} [AF(t+1) - AF(t)]^2}{n-1} \tag{4}$$

The first value of AF, AF(0), is calculated as an average of the available assessment factors for every raingauge.

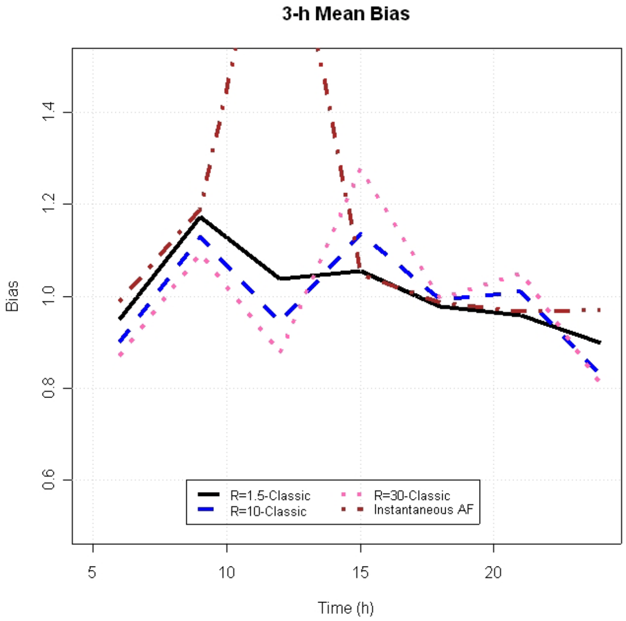

Fig. 2. Mean BIAS.

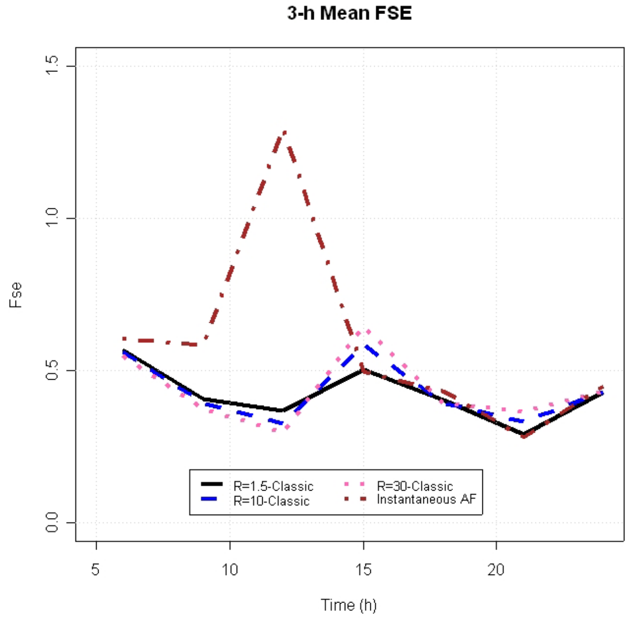

Fig. 3. Mean FSE.

The observed assessment factor, AF_{obs}, is estimated as the ratio between radar-cumulated and raingauges-cumulated precipitation plus a term representing an error following a gaussian distribution with mean = 0 and variance = R :

$$AF_{obs} = AF(t) + v_t \quad (5)$$

The Kalman simulated $AF(t)$, in the hypothesis that we have an observation of AF at time t, will be

$$AF(t) = AF_{\exp}(t) + K\,(AF_{obs}(t) - AF_{\exp}(t)) \quad (6)$$

where K is R and Q dependant.

In this study we've fixed three different values of R: R=1.5, R=10 and R=30, it's important knowing that as R approaches zero, the actual measurement is trusted more and more, while the predicted measurement is trusted less and less.

Some conditions are requested to radar and raingauges data to consider the AF_{obs} obtained a reliable value:

– radar and raingauges precipitation amounts must be larger than 0.6 mm/3 h,

– for stations in a good position (i.e. radar beam height less than 1000 m above sea level with respect to the radar) AF_{obs} is accepted if $|AF_{obs}| < 10$ dB, because otherwise the raingauge is considered unreliable.

In the classic implementation of the filtering algorithm (Welch and Bishop, 2001) a bad AF_{obs} is considered as a missing value, and it doesn't allow to update the estimation of AF. Besides the classic algorithm, a possible different choice is proposed here: a not valid AF_{obs} is replaced by the AF_{obs} at previous instant assuming a sort of persistency hypothesis that could be acceptable in case of stratiform rain as the considered one.

5 Results

The aim of this study is to evaluate whether the correction of radar rainfall fields with Kalman-simulated assessment factors gives good results, and in that case evaluate, referring to the event of 24 November 2002, which is the value of R that gives the best results and which, between the classic Kalman filter or the "persistent" one, works better.

We have generated 7 temporal series of assessment factors for every raingauge: 3 using the classic Kalman filter, 3 using the "persistent" one, and 1 using real observed assessment factors.

In order to study the results obtained using the simulated assessment factors, two classic statistical parameters have been calculated: mean bias

$$\text{mean bias} = \frac{\sum_{n=1}^{N} \frac{R_{rad}(n)}{R_{gau}(n)}}{N} \quad (7)$$

and mean FSE (fractional standard error)

$$\text{mean FSE} = \frac{\sum_{n=1}^{N} \frac{|R_{rad}(n) - R_{gau}(n)|}{R_{gau}(n)}}{N} \quad (8)$$

between AF corrected radar data and 21 raingauges data, not involved in the calculation of assessment factors. In other words 21 raingauges, chosen randomly but well-distributed over Piedmont area, have been excluded from the calculation of rainfall radar field correction with raingauges AF. We imposed the excluded stations to be more than 10 Km far from each other, with a maximum of 10 in good position with respect to the radar. The estimates in these points allow a good evaluation of the Kalman filter performance.

The comparison of results obtained using classic and “persistent” Kalman filter shows that they work in a very similar way, at least for the event of 24 November 2002, probably due to the fact that it was stratiform and quite continuative, so in Fig. 2 and Fig. 3 we’ve represented statistics obtained using classic Kalman only.

The mean bias between the corrected radar rainfall fields and 21 gauges left out is plotted in Fig. 2, the mean FSE in Fig. 3. We observe that, where there’s a good correction using instantaneous AF, the three types (R=1.5, R=10, R=30) simulated AFs work well too, and where the instantaneous AF brings to gross mistakes, for instance at 12 UTC, the Kalman filter smooths the errors. In this case the filter with R=1.5, which gives more weight to the instantaneous observation than to the a priori assessment factor, gives the best results: it’s more stable and doesn’t suffer too much the previous history, as happens for example using other values of R at 15 UTC. Probably the better results with R=1.5 can be addressed to the good disposition of raingauges over Piedmont area and to the type of precipitation, stratiform and uniformly distributed, allowing the observation of many good AF.

6 Conclusions

In this case study general good results in radar precipitation amounts correction using Kalman simulated assessment factors have been observed and in particular a smoothing of gross errors noticed when unreliable observed AF are used. Comparing the results obtained using different values of R, the one with R=1.5 seems to be the best one, probably due to the type of precipitation: stratiform and uniformly distributed. The next step will be an investigation of a convective event, addressed to evaluate whether, in very unstable conditions, the Kalman filtering of AF gives still reliable results and, in that case, which is the best value of R to choose. In fact in the considered case study it seems reasonable a value of R that gives big importance to the observed assessment factors, but in case of convection the available data could be not well distributed and less reliable, so a different value of R may have to be chosen.

If these studies will give good results the next goal will be the operational use of a Kalman filtering implementing algorithm with these benefits:

– smoothing of errors,

– consideration of meteorological conditions variability.

In fact the filtered assessment factors could be calculated using rainfall amounts referred to a smaller number of hours, because the Kalman filter smooths big peaks and errors, thus allowing to take into account the time variability of the precipitation.

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