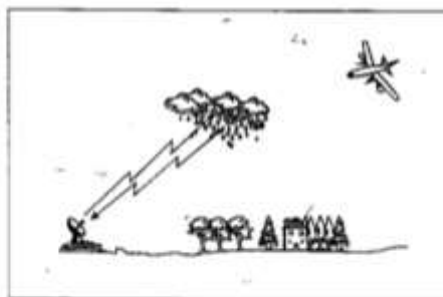


Gaspere Galati (Coordinator)



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EVALUATION OF INTEGRATED PROCEDURE FOR DUAL POLARIZATION RADAR DATA PROCESSING

D. Gnani, L. Baldini, M. Gherardelli, P. Mazzetti, E. Palmisano, L. Facheris

Dipartimento di Ingegneria Elettronica - Università di Firenze
Via di S. Marta, 3 - 50139 Florence - Italy

Abstract

Data acquired by means of a meteorological radar sensor are often corrupted by errors limiting accuracy of quantitative precipitation estimates. This can be due to the presence of ground clutter intercepted by the radar beam, which causes different errors affecting the estimation of rainfall rate and other significant rainfall parameters: indeed ground clutter superimposed to rainfall data and the possible presence of ground relieves shadowing the antenna beam can often occur. A previous evaluation demonstrated that ground clutter can positively be detected by resorting to multiparameter classification of the acquired echoes [1, 2].

In the C-band range of frequencies, which we refer to in this paper radar acquisitions are also strongly affected by attenuation due to propagation of the electromagnetic wave through the storm.

This paper presents an automatic procedure, based on the polarimetric features of the acquired radar data, for detection and correction of such anomalous conditions; its performance are evaluated through its application to data acquired through a C-band radar, located in the neighbourhood of Florence, within a central area of Tuscany (Italy).

Evaluation of this procedure efficiency is made through comparison between rainfall rate estimate derived from radar data and that obtained through raingauges, properly selected among those located over the coverage area of the radar system.

1. INTRODUCTION

The rainfall rate estimate by weather radars is affected by different sources of errors, among these echoes due to backscattering particles different from raindrops can cause an important loss of accuracy. Indeed, the presence of either solid- or mixed-phase precipitation or ground clutter, when intercepted by a low elevation antenna beam, can seriously affect the estimates of different precipitation observables and consequently the rainfall rate evaluation.

Other sources of errors are mainly due to attenuation, intrinsic to radar measurements: attenuation due to beam screening by orographic relieves, attenuation due to propagation through a rain filled medium, which is assumed not significant for S-band radars, while it arises

pressingly when considering data collected by a C-band radar system, because of the higher frequency range.

Some techniques were illustrated in previous papers [1, 2], which exploit polarimetric Doppler radar capabilities for attempting multiparameter classification of dual polarised echoes from rain against clutter and consequent filtering of related data with the aim at obtaining rainfall maps cleaned from ground interfering echoes. When some anomalies of data are detected by applying the discrimination tests, the first step is to recognize the presence and, possibly, the type of these anomalies. Once the presence of ground clutter in the observed resolution cell cannot be considered as the cause of unreliability of data, the comparison of results from the different discrimination tests can emphasize the presence of the other impairing phenomena. Thus this multiparametric analysis of data turns out in an effective tool for detecting and discriminating the different types of phenomena that can affect radar measurements in a rainfall event.

For an easier understanding of this paper contents, hereafter we recall briefly some basic concepts of radar meteorology.

The term "multiparametric" indicates acquisition of different nature parameters, specifically in the radar application field it refers to exploitation of backscattered information within different domains: frequency-, time/space- or polarization domain.

This paper refers to different parameters, obtained by means of measurements: average Doppler velocity, absolute reflectivity both in presence and in absence of precipitation, when the same polarization is set in transmission and on reception, differential reflectivity that account for different behaviour of raindrops when illuminated by differently polarized waves.

The absolute reflectivity Z is defined as:

$$Z = \left(\frac{\lambda}{\pi^2 |K|^2} \right)^2 \int_0^{D_{\max}} \sigma_{\text{eff}}(D) N(D) dD \quad (\text{mm}^6 \text{m}^{-3})$$

where D_{\max} is the largest raindrop dimension, λ is the wavelength (mm), $|K|^2$ is the refractivity factor of water for C-band propagation in our case, $\sigma(D)$ is the equivalent radar cross section of raindrops, D is the diameter of an spherical drop which volume equals that of actual raindrop, $N(D)$ is the raindrop dimension distribution [2].

When acquiring data related to absolute reflectivity we obtain different values for the same precipitation cell, which account for the different polarization used for measurements, the same in transmission and on reception.

The differential reflectivity parameter, Z_{DR} , was first utilized by Seliga and Bringi [3], who showed its importance for producing improved estimates of rainfall rate, R , as compared to the conventional radar measurement schemes.

The Z_{DR} parameter is defined as:

$$Z_{\text{DR}} = 10 \log (Z_{\text{H}}/Z_{\text{V}}) \text{ (dB)}$$

where the parameters Z_{H} and Z_{V} are the radar reflectivity factors ($\text{mm}^6 \text{m}^{-3}$) obtained with horizontal and vertical polarizations [1], respectively.

Basically, the differential reflectivity radar technique for estimating rainfall parameters utilizes the anisotropy of a region of space filled with waterdrops, with respect to the electromagnetic scattering properties. Two factors combine to establish this anisotropy:

- Waterdrops take the form of nearly oblate spheroids as they fall through the atmosphere, and their degree of eccentricity increases with equivalent drop size; thus, the horizontally and vertically polarized backscattering cross sections of raindrops differs considerably when their size is larger than 0.5 mm. This difference increases as the raindrop size increases.
- Waterdrops fall with a high degree of alignment with their symmetry axes (minor axes) along the vertical axes).

In the Rayleigh regime, owing to those properties, the horizontal polarized radar return power from a rain-filled scattering volume, on average, exceeds the return from a vertically polarized wave. This effect is the basis of the dual-polarized differential reflectivity technique of radar rainfall estimation that introduces the Z_{DR} radar observable in addition to Z_{H} for estimating parameters of the raindrop-size distribution.

Exploitation of frequency domain requires collection of data relating to precipitation mass motion: when the illuminated region is characterized by uniform reflectivity it is possible to assume that the power spectrum of the received signal is characterized by a Gaussian distribution. Thus, average velocity v_m and Doppler standard deviation σ_m are necessary and sufficient parameters for definition of Doppler Spectrum. Methods for spectral analysis of precipitation are then interested in evaluating both parameters above, which give a complete information on power spectrum.

In this paper we consider the possibility of detecting and then correcting errors which affect measured data, collected by means of a coherent C-band radar system in Tuscany (Italy). Corrected parameters are then compared with those collected by raingauges located within the radar coverage area, for an efficiency evaluation of correction algorithm which we propose for a complete restoration of data. The raingauges' sites are characterized by different orographic relieves and can result as being associated with radar data suffering from the beam shadowing phenomenon.

The first part of the paper reports characteristics of measurements, together with the radar system configuration, its site, the raingauges' number and allocation with a brief description of the surrounding orography. The second part of this paper recalls discrimination techniques previously proposed [1, 2] for clutter detection in S-band radars. The third part is devoted to correction procedure for removing disturbances on acquired data. Finally results of comparisons between rainfall rate estimates by raingauges' data and corrected rainfall rate estimates derived by radar acquired parameters, are presented and results are illustrated, aiming at evaluating efficiency of correction algorithm.

Interesting consequences of this study are pointed out at the end of this paper. Specifically, this approach allows also to select those raingauges, providing reliable data, which can profitably be correlated with the radar data in the presence of rainfall, when calibration through data integration is applied.

2. THE RADAR MEASUREMENT SET

2.1 The radar system and its site

The main characteristics of the basic configuration of the radar sensor utilized for measurements are here briefly described. Operating terms for measurement are even specified.

The employed radar unit, called POLAR-55C, is a C-band coherent meteorological dual linear polarisation system using a high performance antenna. Its main characteristics are listed in Table 1.

The radar system, owned by IFA-CNR, was installed in Montagnana, which is about 17 Km far from Florence, in a central area of Tuscany. The radar site allows a good visibility of the Arno river basin, which is needed for experiments planned within the 'Arno Project'. This Project was started in 1986 and is jointly supported by the National Group for the Prevention of Hydrological Disasters and the Minister Co-ordination of Civil Protection: the main task of this project is the study and experimentation of optimal solutions for use and integration of complementary environment sensing techniques in order to devise a real-time monitoring system for Arno river flood forecasting.

Transmitter:	
frequency	(5.40 - 5.65) GHz
peak power	> 500 kW
pulse width	0.5 - 1.5 - 3.0 ms
P R F	1200-600-300 Hz
average power	100-450-450 W
Antenna:	
aperture diameter	4.57 m
shape	Circular
gain	45.5 dBi
Receiver:	
n. of channels	3
response	log. or linear
noise figure	5.5 dBi

Table 1: Basic configuration of the radar set.

The initial radar configuration was then updated with the implementation of a double receiver (for reception of polar and cross-polar signals), a Doppler receiver and a new radar signal processor that allows the use of a clutter rejection filter, in addition to more accurate estimates of both the reflectivity and Doppler parameters.

2.2 Description of radar data from measurements

For the purpose of evaluation and validation of the data processing procedure proposed in this paper, we have considered and processed data selected from those acquired by means of the above radar system, during a meteorological event featuring strong precipitation, which occurred during the night of October 3-4, 1992. Such a precipitation caused the flash flood of

both some urban torrents and some Arno river confluents. These data have been collected in the PPI acquisition mode, with elevation angle of about 1.8 degrees, while the acquired scans were time-spaced out about ten minutes. Additional notes on the acquisition mode are reported in Table 2, where v_m and σ_v indicate measurement of the average value and the standard deviation of radial velocity, respectively, as derived from the Doppler spectrum of the observed phenomenon.

Mode	ALL-MODE
Polarization	Alternate H-V
Pulse width	Short, 0.5 s
P R F	1200 Hz
Collected Parameters	Z _{dt} Z _{nv} v _m σ_v
Integrated pulses	64 pulses
Antenna rotation rate	360 deg/min

Table 2: Acquisition mode during measurements.

Different digital maps were picked up from measured scans, which illustrate values of different parameters characterizing precipitation. They refer to a complete radar scan thus showing the entire radar coverage at a set elevation angle. For the classification tests dry maps of the coverage region are needed too: such registrations were carried out on July 28, 1992, in different acquisition modes and with many elevation angles.

2.3 Raingauge network

We compared data obtained by radar observations with those collected by raingauges: a network of 43 telemetered raingauges is sited over the Arno basin, mainly upstream of Florence (within Sieve basin, Valdarno and Casentino areas). Such raingauges are connected with Tuscany Region Offices (in Florence) and "Servizio Idrografico e Mareografico" in Pisa. Rainfall depth measurements are then made available at each raingauge location, at the same time and with a sampling period of 15 minutes.

Two raingauges, placed in the radar system coverage area, have been selected for our purposes; selection has been carried out basing on characteristics of orography surrounding their sites: a gauge site is illuminated by the radar antenna beam in clear air (Stia), the other gauge's site (Vallombrosa) is characterized by strong clutter.

3. CLASSIFICATION TESTS

In previous papers some algorithms for multiparameter radar data classification were proposed [1,2], mainly aiming at clutter detection. Such algorithms give positive results for detection of unreliable precipitation data caused by clutter when applied to experimental data from a S-band polarimetric radar.

The used classification algorithms are based on "elementary tests", applied to single parameters, independent of each other, extracted from the multiparameter radar measurements data. Improved classification is actually operated by resorting to the "combined tests", which are a proper logical combination of the "elementary tests".

In this paper these tests' capabilities to detect also error caused by beam shadowing, as well as attenuation due to strong precipitation, as occurring in C-band radars, are considered and illustrated.

3.1 The elementary tests devised for clutter detection

The processing steps of the different elementary tests are summarized hereafter: for further details on these techniques the reader is referred to [1,2].

1. *Static techniques.* The analysis of radar coverage dry maps, which report absolute reflectivity parameters (for instance Z_H data) measured within each cell of the radar coverage when no precipitation occurs, allows to estimate intensity and spatial distribution of ground clutter.

The related test which compares powers of wet (i.e. in presence of rain) and dry maps (i.e. in absence of rain) from the same area is, up to now, the most used method for detection of radar cells contaminated by ground clutter. Those cells, where the difference between "wet Z_H " and "dry Z_H " is lower than a fixed threshold (15 dBZ in our case) are classified as clutter. This test shows, in general, good performance, even if a fully successful detection of clutter is generally obtained only for central areas of zones filled by ground clutter.

2. *Doppler spectrum analysis.* The backscattered signal from land is generally characterized by a spectrum with zero mean and small deviation, which is due to both vegetation movements and random signal fluctuation. The precipitation signal can have a large spectrum, which is larger in the C-band frequency range than in the S-band, with an average frequency depending on radial velocity of precipitation, which is related to falling velocity of raindrops and front movement direction. A satisfactory discrimination is realized when the spectra of ground and rain are not superimposed.

The test related to this kind of analysis classifies, as "clutter cell", that resolution cell from each sub-area, where the absolute value of mean velocity is less than a standard threshold, thus assuming zero mean velocity for the ground clutter. Indeed this test sometimes fails: this is the case that a very low radial velocity of precipitation front occurs (near null Doppler frequency), which implies that the associated cells are classified as contaminated even if no ground clutter is present.

3. *Polarimetric techniques.* These techniques are here mainly based on the features of the Z_{DR} and Z_H parameters [3].

Typical patterns of these parameters' values in presence of "rain alone" can be thus synthesized [1]: low values of Z_H (because of limited dimensions and number of raindrops); positive and low values of Z_{DR} (because of shape and alignment of rain particles); locally uniform spatial distribution of Z_{DR} ; statistical variations of Z_H parallel to those of Z_{DR} .

In the presence of "ground clutter", a large variety of shapes and dimensions of intercepted obstacles causes a low correlation between measured Z_H and Z_{DR} . Moreover these parameters can take on high values. Spatial non-uniform and negative values of Z_{DR} are characteristic patterns of ground clutter superimposed to rain. A plain representation of Z_H - Z_{DR} parameters, reported in Fig. 1., allows to draw a typical clustering region, which is shadowed in the picture, where each point pertains to rain derived parameters, while data points outside that region are obtained from contaminated data.

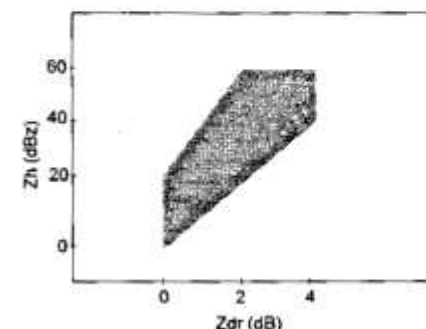


Fig. 1 - Scatter plot reporting Z_H values as functions of Z_{DR} values

Two different polarimetric tests were suggested [1]:

- "Z_{DR} spatial variability test". Basing on the property that differential reflectivity Z_{DR} shows a larger variability in the presence of clutter, small areas with high range of values for Z_{DR} are classified as contaminated. A check is performed on the standard deviation of Z_{DR} in moving windows which size is 3 azimuth cells times 3 range cells, scanning the entire radar image. If the standard deviation is greater than a threshold, the central element of the window is suppressed. This test works well only when the observed values of Z_{DR} are not large.
- "Rainfall cluster test". A region of the plane Z_H - Z_{DR} is selected, which is characterized by points where pair Z_H - Z_{DR} is typical of rain: when a radar cell shows a Z_H - Z_{DR} pair that falls outside this region, it is classified as anomalous datum.

3.2 Effectiveness of the elementary tests

Elementary tests, as introduced in [1], mainly aim at discriminating rain derived echoes from those obtained by ground clutter, but their effectiveness can fail in the presence of additional sources of errors. In particular, this is the case of C-band radar, especially when operating in a complex orography environment. In such a case, additional and relevant problems arise in the presence of high intensity rainfall, causing cumulative signal attenuation along propagation path and when the beam shadowing occurs, due to interception of ground relieves.

Heavy precipitation causes indeed strong attenuation of the propagating e.m. wave, which is different for the horizontal and vertical component waves, thus causing a progressive reduction, along path, of the observed values of both Z_{DR} and Z_H . The polarimetric tests necessarily suffer from these effects. Their performance in rain/clutter discrimination degrades due to alteration of Z_{DR} (anomalous, low, also negative, values are observed), but also due to

the associated displacement of the clustered Z_H - Z_{DR} area, which causes the "cluster test" detecting an anomalous datum even in the presence of rain alone. Conversely the high attenuation causes that the value of the estimated rainfall rate, as obtained from transformation of the radar reflectivity data, is considerably lower than the actual one.

Moreover in the case of high intensity rainfall, Z_H and Z_V can be higher than that of ground clutter, thus rainfall can mask the presence of interfering clutter. In this conditions both the polarimetric and the Doppler spectrum analysis tests can indeed sometimes fail in ground clutter detection, although ground clutter is still significantly affecting accuracy of radar precipitation measurements.

Even beam shadowing can reduce intensity of the radar signal thus affecting radar measurements accuracy, as it is typically occurring along the propagation path. Thus, in this case, typical errors are wrong estimates of rainfall rate values and missed detection of ground clutter.

Some more considerations can be devoted to the spatial variability test, which doesn't seem suffering from beam shadowing and attenuation effects in data classification, if both a small window size is used for processing and equal antenna patterns for the horizontal and vertical polarizations are applied, because it is sensitive to spatial gradient of parameters alone.

Even if classification processing suffers of problems highlighted before, comparison among results obtained by the different elementary tests can help in detecting the presence of beam shadowing or intense rainfall.

3.3 Combined tests

An improvement in data discrimination can be achieved when the elementary techniques are combined, aiming at exploiting the complementary classification properties of the different component tests and, in some respect, at compensating their errors, when singly operated.

The first combined algorithm, that we call "Complex test 1", is reported in Fig. 2. It can give three outcomes: 'clutter', 'rain' and 'rain with unreliable estimate'. The last output occurs when no alternative choice is acceptable because of a contrast between results from polarimetric tests and those from static test.

A simplified test was also proposed ("Simplex test 1"), which does not require Doppler radar capability. It is a simplified version of the combined algorithm above, as depicted in Fig. 3, which utilizes only three elementary tests, among those above described, providing only two outcomes ("clutter" and "rain"). Obviously the performance of the simplified test is not so good as that of the composed one, but the cascade of the polarimetric tests is still capable of assuring good compensation of errors.

In addition to the above tests, in this paper we consider two modified versions of them: their block diagrams are reported in Figs. 4 ("Complex test 2") and 5 ("Simplex test 2"). Both tests generate three different and alternative outcomes: "rain", "clutter" and "rain with unreliable estimate".

In the first algorithm all elementary tests are utilized: "clutter" is detected only when both Doppler based and static tests agree, otherwise the polarimetric tests are carried out; then "rain" is detected when both the polarimetric tests agree. The second figure shows a very simple test, which is based on the use of the polarimetric elementary tests only, which can thus be generated by a non-coherent radar system too.

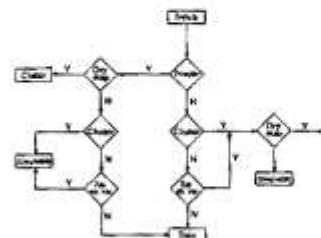


Fig. 2 Complex test 1

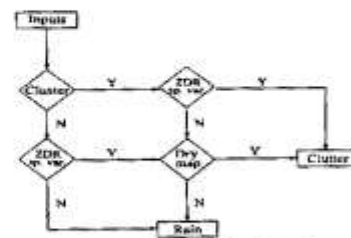


Fig. 3 Simplex test 1

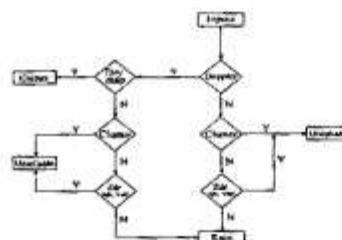


Fig. 4 Complex test 2

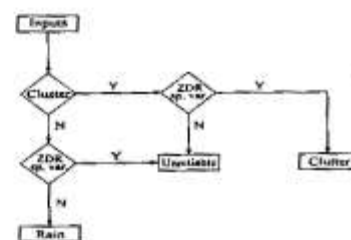


Fig. 5 Simplex test 2

4. PROCEDURE FOR CORRECTION AND RESTORATION OF CORRUPTED RADAR DATA

In this paper section a procedure is presented for testing and restoring quality of data acquired through a meteorological radar, which receiver exploits multiparameter processing.

Three different causes of errors can corrupt data quality: ground clutter, beam shadowing due to ground relieves interception and signal attenuation due to propagation of e.m. wave along path in a rain filled medium.

The first cause of errors, the presence of ground clutter superimposed on meteorological echoes, was widely analysed in previous papers [1, 2], which highlighted that different behaviors of Z_H and Z_{DR} parameters characterize rainfall data and ground clutter data, specifically Z_{DR} - Z_H scatter plots of rainfall are clustered within a specific area (see Fig. 1); this is not the case for ground clutter's. Parameters' reconstruction of the contaminated area is carried out starting from contour cells. A section of 7×7 cells (about 20 Km^2) is selected around the considered cell. Each cell contribution is suitably weighted by coefficients, which are the normalized distances from the window center. This procedure assures good results

when the contaminated area is small, because in this case the estimated value of the contaminant cell parameter agrees with local spatial statistical characteristics of next cells. When parameter of the contour cells are reconstructed, the contaminated area is restricted and a new contour can be processed.

With reference to the second phenomenon, strong attenuation can be revealed on both horizontal and vertical components of the wave backscattered by the area under observation, thus causing a quite unaltered value of differential reflectivity and a lower value of absolute reflectivity. The expected effect on Z_{DR} - Z_H plots is a shift of the shadowed region in the direction of Z_H axis.

Once the presence of screening is detected, the simplest way is to determine the percentage of blocked beam by means of a digital terrain model (DTM) and an atmospheric propagation model, but such a method is critical as far as screening due to the nearest obstacles is concerned.

In the present case a geometrical algorithm is used. The theoretical position of radar beam upon the terrain level is evaluated, resorting to a regional DTM, consisting of a matrix of quotes referred to 0.4×0.4 km resolution UTM grid.

Once ground clutter contamination is detected at a given position, individuated by the corresponding radar azimuth and range r , for the given elevation θ , the theoretical height of the centre of the beam can be computed. The altitude of the corresponding surface point below the radar beam is evaluated.

The attenuation correction coefficient can then be computed. The radar beam was simulated through a $N \times M$ matrix, which elements were weighted by means of a bidimensional Gaussian function, because the same Gaussian pattern is assumed for both H and V polarization where.

The estimate of the attenuation affecting the absolute reflectivity is thus expressed by the ratio between the sum of contributions by non-obscured beam cells and the total power radiated.

The correction of attenuation due to propagation through a rain filled medium is assumed to be not necessary for S-band radars, while it is needed for C-band radars, in particular if dual polarization is employed. In fact, in the case of differential reflectivity technique, both Z_H and Z_{DR} are affected by a total attenuation, positive and increasing with distance, depending on rainfall intensity along the path. Such effects affect heavily radar data, especially in the presence of high rainfall intensity.

The scatter plots obtained in this case showing a shift of the shadowed region along both directions of the representation plane.

Advanced methods for the correction of propagation attenuation refer to phase measurements, primarily to the specific differential propagation phase [5] which, on the other hand, are not frequently available on commercial radar systems. Therefore, if one assumes to have only incoherent observables at disposal, he should employ recursive techniques in order to correct attenuation along one radar ray by scanning it, cell by cell. Specific attenuation is derived from reflectivity and employed for the correction in the current cell and the evaluation of total attenuation along each radar ray.

The first recursive method for C-band monoparametric radars was introduced by Hildebrand [6], while later Aydin et al. [7] proposed a similar procedure using also Z_{DR} values. The main problem in such methods is to evaluate the specific attenuation coefficients of the relationships that are assumed as models for relating specific attenuation to radar observables Z_H and Z_{DR} , and possibly to other parameters like temperature. Since measured

reflectivity factors are corrupted by attenuation, Z_H and Z_{DR} values to be introduced in the aforementioned relationships should be previously corrected by removing the cumulative attenuation estimated by means of the same method in range bins closer to the radar along the same ray. Other authors also employed the same scheme, but utilizing several different relationships between specific attenuation and reflectivity, differing for the way they were obtained (experimental or theoretical), for the kind of the conversion function and their coefficients. Such a correction scheme can be summarized by the following equations:

$$Z_{H_c}^c = Z_{H_m}^m + 2\Delta r \sum_{i=k}^{n-1} A_{H_i}$$

$$Z_{DR_c}^c = Z_{DR_m}^m + 2\Delta r \sum_{i=k}^{n-1} A_{DR_i}$$

where superscripts c and m stand for "corrected" and "measured", respectively, while the subscript n is the index for the n -th range bin, which depth is Δr , and where A_{H_i} and A_{DR_i} are specific attenuations in dB/km, computed by means of relationships relating them to the reflectivities obtained at the preceding range bins.

The critical aspect of such cumulative schemes is related to their instability, which leads to unreliable and anomalous corrected reflectivity data. This may be due either to initial conditions (incorrect or missing radar calibration) or to the occurrence of anomalous data along the radar ray, particularly when they give rise to very high Z_H values. Since the procedure starts from the closest range bin where rainfall is detected, the main source of instability could be indeed an incorrect radar calibration. Aydin's algorithm requires the calibration error to be within 1 dBZ for Z_H and 0.2 dB for Z_{DR} . Besides radar calibration problems, the presence of anomalous data, particularly as far as Z_{DR} is concerned, induce physically not consistent values once they are substituted into the aforementioned conversion relationships. These additional problems occur in the presence of ground clutter, mixed-phase precipitation and beam screening. Thus, before correcting reflectivity data by means of recursive techniques, it is quite advisable to detect/classify anomalous data and to correct beam screening effects. In particular, the screening can be critical in the presence of heavy rainfall, since attenuation correction becomes critical, leading to excessively overestimated corrections of Z_H values which may cause the correction algorithm to diverge.

In this context, it is rather obvious that a correct hardware calibration of the radar receiving system is mandatory and preliminary to any other reflectivity correction scheme. In particular, effectiveness of the attenuation correction scheme depends on such calibration: for the POLAR 55C, a systematic bias in measurements was assumed of 2 dBZ and 0.2 dB, affecting Z_H and Z_{DR} respectively.

5. COMPARISONS BETWEEN RADAR DATA AND RAINGAUGES DATA.

The main problem in comparing data from raingauges to those from radar, is due to the different characteristics of sampling, both in time and in space domain, by these two sensors.

Indeed raingauges are characterized by a time integration period of fifteen minutes, during which the rainfall depth is cumulated. Raingauges are not uniformly displaced and far from each other over Tuscany region. Moreover their sites often are not significant for comparison with radar data.

Conversely, the radar system supplies instantaneous estimates of rainfall rate with time intervals that are not uniform during measurements, but they last less than fifteen minutes. Data are collected from a large area, with maximum range up to 122.5 Km far from Montagnana, with an azimuth resolution of 0.96 degrees.

Data processing is thus necessary for comparing data collected from these different sensors. Each rainfall depth sample from raingauges is averaged over the sampling period (15 min.), thus obtaining samples of the average rainfall rate over each single raingauge.

All data samples obtained by the radar system from the resolution cell, where the considered raingauge is sited, are considered and reported as function of acquisition time; a continuous curve joining the samples' extrema is drawn and the time axis is subdivided into fifteen minutes intervals, matching those of raingauges: the subtended areas are computed and averaged over the related time interval (i.e. fifteen minutes).

In this way comparable time-sequences of the parameters are obtained.

While raingauge data are average rainfall rate values, radar collected data refer to absolute and differential reflectivity values, which have to be converted to rainfall values. For conversion purposes two different expressions were tested. A first attempt was carried out by resorting to Marshall and Palmer standard expression:

$$Z_H = 200 R^{1.6}$$

As generally known, this expression underestimates the rainfall parameter, R , in the presence of heavy precipitation (for rainfall rates greater than 10 mm/h).

The second expression was studied and presented by Gorgucci et al. [8], who obtained it by minimizing the difference between rainfall cumulative distribution function from radar and that from raingauges, for the rainfall event presented in this paper:

$$Z_H = 42.6 R^{1.5625}$$

Both expressions relate the rainfall rate parameter with the measured absolute reflectivity. These expressions allow the use of absolute reflectivity alone, thus directly relating rainfall rate to received power and emphasizing losses of power and their causes. The choice of these expressions, among others potentially even more accurate and using (Z_H-Z_{DR}) relationships, is due to the unreliability of measured data, which are affected by significant errors. Because Z_{DR} parameter is more sensitive to the different causes of errors and mainly to attenuation due to propagation through rainfall, which differently affects the horizontal and vertical components, the rainfall rate estimate is here evaluated through functions of the absolute reflectivity alone.

For an appropriate and meaningful evaluation of correction procedure efficiency, in the following pictures four curves, representing rainfall rate as a function of acquisition time, are

reported: the first for measurements from raingauge (continuous line), the second (plus-symbol line) and the third (asterisk-symbol line) for those from radar sensor, evaluated by resorting to Marshall and Palmer relation and to Gorgucci's expression respectively. The last curve (X-symbol line) reports Gorgucci's rainfall rate estimates corrected from possible errors.

At the bottom of the figure classification tests' results are transcribed: the table of these results thus shares the time axis with the rainfall rate curves. This type of representation would not be corrected because rainfall rate data, as already explained, refer to average values, while classification tests applies to punctual data, nevertheless we think that a simultaneous comparison between those results and rainfall rate curves, can be useful for evaluation of both tests' efficiency and data quality, and it can help interpreting applied corrections.

Different symbols denote the different outcomes of tests: when a resolution cell filled of rain is detected a "R" symbol is used, while a "C" symbol is utilized for clutter contaminated datum, when rain with unreliable estimate is detected the "U" symbol is used. When no rain is detected, the "N" symbol is used in the table. The symbol "A" is introduced as possible output of the cluster test alone: it denotes data which are characterized by parameters atypical for rain, which can then be classified as anomalous.

At the top of figures, the height of ground profile above the sea level, between the radar sensor and the raingauge at hand, is reported as a function of distance from the radar site. Three lines are also reported on the picture, which refer to the antenna 3dB-beamwidth (external lines) and to the elevation angle (central line) during radar acquisition: the radar system was acquiring data from resolution cells with an average elevation angle of about 1.8 degrees, but sudden jumps in the elevation were observed during measurements, which caused the antenna pointing a different volume of raincell for the time of an acquisition. Thus produced errors were removed by resorting to interpolation procedures.

Fig. 6 refers to data collected by the raingauge named "Stia", characterized by good orography around the raingauge site and by no-beam shadowing, as also shown by the height profile at the top of the picture. The picture shows a good correlation among all the rainfall rate curves, even if the Marshall and Palmer expression exhibits an evident underestimation of rainfall rate.

The radar derived data, even those obtained through Gorgucci's relation, appear strongly attenuated along the propagation path through rainfield, while the corrected curve nearly matches the raingauge curve, thus testifying good performance of correction procedure.

Results from classification tests appear well grounded for almost all the techniques, which detect rain in the presence of not intense precipitation event, while no data are reported in the absence of precipitation. In the presence of heavy rainfall rate, as detected by the raingauge, the combined tests classify data as atypical of rain (U symbol): this is mainly due to the fact that attenuation during the propagation path operates differently on the horizontal and vertical polarized components of the wave, thus modifying the differential reflectivity acquired by the radar receiver, that cannot anymore be classified as typical of rain. For this reason the cluster test always fails its classification in the presence of heavy rain.

From an analysis of radar data, we can see that the radar system failed acquisition at two times: that denoted as 1365 minutes past midnight and that 1440 minutes past midnight. Indeed acquisition problems were reported during recording of related data.

Fig. 7 refers to data collected by the raingauge named "Vallombrosa". This is a clear example of the presence of strong ground clutter within the resolution cell surrounding the raingauge. The rainfall rate curve from the raingauge reveals an intense precipitation over the

sensor from 1340 to 1440 minutes past midnight, while the radar system records data even outside this time interval, which are due to strong ground clutter. However during the precipitation event, radar data agree with those from raingauge even if strongly attenuated because of the same causes previously mentioned. When correction is applied on radar data, two different effects can be observed: increased values of rainfall rate due to correction of two-way propagation, decreased values of the radar curve when clutter is detected. However the corrected curve doesn't match that of raingauge, even if better profile than that from not processed data can be observed: higher levels of the corrected curve than those of raingauge's can be observed in the presence of not intense rainfall, due to uncompleted clutter cancellation; while lower levels are obtained for intense rainfall, because correction procedure is sensitive of the presence of strong clutter. However better correlation between rain gauge curve and radar curve is obtained by means of correction processing of data.

In this case the classification tests give different results and thus showing a different efficiency. If we consider only the combined tests, we can note that "complex test 1" and "simplex test 1" classify as clutter almost all processed data, so that no data during heavy rainfall could be used for estimating rainfall rate. The corrected tests ("simplex test 2" and "complex test 2") classify as clutter only those data collected outside the peak of precipitation, while data are classified as "U" when precipitation occurs: it means that the absolute reflectivity is a reliable datum because precipitation intensity completely masks the ground clutter, while the differential reflectivity is unreliable because of attenuation. Results from classification show two anomalies, specifically at 1440 min. and at 1550 min. past midnight: the second is due to a lack of acquisition by the radar system, the first denotes a rainfall datum in the absence of contamination by ground clutter, which is due to a sudden jump in the elevation of the acquiring antenna, which is acquiring at 2.5 deg. of average elevation angle, thus pointing only the precipitation bank.

The above analysis was performed also for other raingauges, among which those characterized by strong beam shadowing, in the same events.

Some deviation in results of performance evaluation were encountered, when the Z-R conversion law was not fitting well local rainfall. However, in general results have generally confirmed the effectiveness of such procedure.

6. CONCLUSIONS

In this paper the efficiency of a correction procedure of data collected by means of a coherent C-band polarimetric radar system in Tuscany (Italy), is evaluated through comparison with data collected by two raingauges located within the radar coverage volume. The selected raingauges' sites are characterized by:

- strong clutter;
- presence of strong precipitation causing strong attenuation along the propagation path.

These conditions have thus allowed an evaluation of data classification efficiency, which significantly extend the evaluation made in [1, 2], only referred to ground clutter detection in the S-band frequency region, to the case of C-band dual polarization coherent radar. The presented results demonstrate also the ability of proposed tests to identify anomalous data due

both to partial beam blockage, and to attenuation through rain filled media, which for C-band radar systems can cause strong errors on rainfall estimates.

The comparison among results obtained by the different tests, also based on the analysis of data matching from radar and raingauges, highlights that decisive modification in the original algorithms significantly improves performance of radar data classification, and a new simplified test can be used with quite good results.

The presented study reveals useful not only for the check of radar data reliability by itself, but also for proper selection of calibration sites with raingauges: the calibration procedure based on integration between radar and raingauge can indeed be bounded to those raingauges associated with reliable radar data.

6. ACKNOWLEDGEMENT

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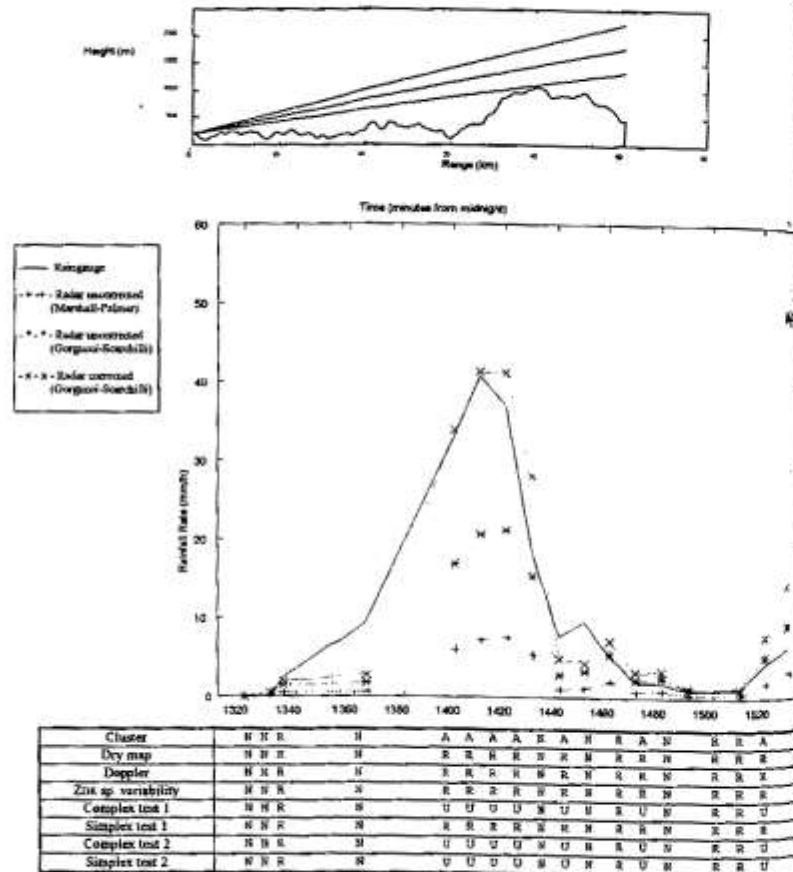
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Rain gauge n. 2 (Stia)

Shadowing

(range = 50.2 km, $\theta = 71.4^\circ$, height above sea level = 461 m)



C: Cluster
A: Anomalous datum

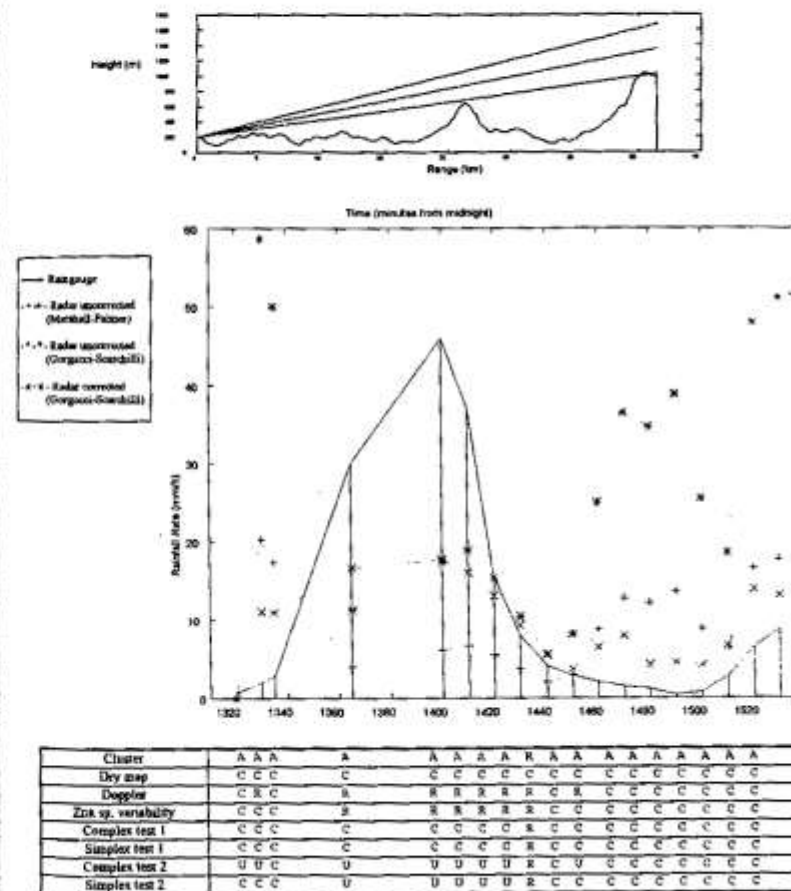
U: Rain with unreliable estimate
R: Rain

N: No rain

Rain gauge n. 23 (Valkumbrosa)

Strong cluster

(range = 36.4 km, $\theta = 77.1^\circ$, height above sea level = 982 m)



C: Cluster

U: Rain with unreliable estimate

N: No rain