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Exploring single polarization X-band weather radar potentials for local meteorological and hydrological applications

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SUMMARY

The aim of this study is to evaluate the potential use of a low-cost single polarization X-band weather radar, verified by a disdrometer and a dense rain gauge network, installed as a supporting tool for hydrological applications and for monitoring the urban area of Palermo (Italy). Moreover, this study focuses on studying the temporal variability of the *Z–R* relation for Mediterranean areas. The radar device is provided with an automatic operational ground-clutter filter developed by the producer. Attention has been paid to the development of blending procedures between radar measurements and other auxiliary instruments and to their suitability for both meteorological and hydrological applications. A general scheme enveloping these procedures and achieving the combination of data retrieved from the weather radar, the optical disdrometer, and the rain gauge network distributed within the monitored area has been designed.

The first step of the procedure consists in the calibration of the radar equation by comparing the match between the radar raw data and the disdrometer reflectivity. The second step is the calibration of the *Z–R* relationship based on the retrieval of parameters that optimize the transformation of disdrometer reflectivity into rainfall intensity, starting from the disdrometer rainfall intensity measurements. The *Z–R* calibration has been applied to the disdrometer measurements retrieved during a 1 year observation period, after a preliminary segmentation into separated rainfall events. This analysis allows for the characterization of the variability of the *Z–R* relationship from event to event, deriving some considerations about its predictability as well. Results obtained from this analysis provide a geographical specific record, for the Mediterranean area, for the study of the spatial variability of the *Z–R* relationship. Finally, the set of operational procedures also includes a correction procedure of radar estimates based on rain gauge data.

Each application has been evaluated with reference to its suitability in supporting proper monitoring usage, with emphasis on the readiness of observations, and hydrological modelling, where the robustness of the quantitative estimates is focused.

1. Introduction

Precipitation measurement systems have experienced relevant advances during last years, especially those from the remote sensor applications. The most important innovations come up from the satellite precipitation framework, mainly due to more robust analyses and new satellite systems such as the GPM (*Global Precipitation Measurements*) satellite system supported by the *National Aeronautics and Space Administration* (NASA) and the *Japan Aerospace Exploration Agency* (JAXA). Main innovations proposed for the field of the ground-based measurement systems, are related particularly to the role of spatial refinement of measuring networks, the development of multi-sensor systems, and the technological advances of measurement sensors. Among these, weather radar systems have kept being a source of new estimation insights, thanks to the development of dual-polarization systems, network radar systems, and new radar technologies.

The widespread of X-band sensors can be considered one of the most relevant development of weather radar technologies, because of the possibility of monitoring local areas continuously, with fine spatial and temporal resolutions, and using affordable devices with reduced economic resources suitable for small monitoring systems. While C and S bands weather radar systems are installed for the monitoring of extended regional areas, X-band devices are

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well-suited for research purposes and for the monitoring of precipitation events in limited areas. Such systems are nowadays available from different producers that offer X-band instruments with several features and low costs. Furthermore, the possibility to design networks of different and heterogeneous sensors has been explored for the realization of monitoring and forecasting systems in the field of hydrological risk and for other hydrological applications (e.g., McLaughlin et al., 2009; Wang and Chandrasekar, 2010).

Most of the studies focused on X-band radars systems usually refer to dual-polarization devices that, as already explored with other bands, reveal relevant features inherent the identification and the classification of targets and the quality of final products (e.g., Zrnic, 1996; Doviak et al., 2000; Bringi and Chandrasekar, 2001; Matrosov et al., 2014). Nevertheless, single polarization X-band instruments have been recently made available with reduced costs and some operational and scientific limitations (Rollenbeck and Bendix, 2006, 2011).

The *Department of Civil, Environmental, Aerospace Engineering, and Materials* (DICAM) of the University of Palermo (Italy) has recently developed a prototypal rainfall monitoring system supporting an *Early Warning System for Rainfall Triggered Landslides*, realized within the Italian National Research Project SESAMO (*SistEma informativo integrato per l'acquisizione, geStione e condivisione di dati AMbientali per il supportO alle decisioni* – Integrated Information System for the acquisition, management, and sharing of environmental data aimed at decision making). The weather monitoring system consists of a single-polarization X-band weather radar, a rain gauge network distributed within the urban area of Palermo (Italy), an optical disdrometer, and other auxiliary instruments.

The measurement system offers the possibility of supporting several applications ranging from the real-time observation of precipitation event dynamics (e.g., for monitoring activities) to the estimate of precipitation inputs for local hydrological models. Depending on these applications it is possible to change the setting of the system in terms of sensors blending procedures and managing of data. Hereafter, these groups are synthetically referred to as "*meteorological*" and "*hydrological*" applications, respectively. In particular, it is assumed that for meteorological applications the emphasis will be on the observation of main features of events and their evolution in space and time, e.g., for risk management operations. For such a class of applications, the weather radar mainly provides details about the spatio-temporal depiction of the events as they are retrieved from radar maps. Conversely, when the precipitation measurement system is used for hydrological applications, the main goal will be the processing of congruent quantitative precipitation estimates.

The most important sources of uncertainty in weather radar quantitative estimates, independently of the radar band, include the radar equation miscalibration (i.e., the relationship between physical variables involved in the radar system), the calibration and the variability of the *Z–R* relation, the range degradation, the vertical variability of hydrometeors and the attenuation besides the ground clutter, the beam blockage, and the partial beam already mentioned. For an exhaustive description of weather radar estimates uncertainty sources the reader can refer to Andrieu et al. (1997) and Villarini and Krajewski (2009).

One of the most relevant procedure for the correction of weather radar measurements concerns the identification and correction of ground clutters, beam blockages, and partial beams. Several methodologies have been proposed in literature with this aim (e.g., Moszkowicz et al., 1994; Joss and Lee, 1995; Pamment and Conway, 1998; Michelson and Sunhede, 2004; Germann et al., 2006; Berenguer et al., 2006).

The weather radar installed in the monitoring system of Palermo is provided with an anti-clutter filter developed by the producer EnviSens Technologies (Allegretti et al., 2012). This filter is intended for operational usage and is not explicitly provided to end users. Nevertheless, the filter can be deactivated allowing for the retrieving of raw measurements; a customized ground-clutter filter can be applied at user-level at a later stage.

Among the remaining elements of uncertainty, the radar miscalibration and the *Z–R* relationship calibration have a strong impact on final precipitation values since they can introduce relevant bias and other errors. The accuracy of the equation for the radar calibration relies on the exact knowledge of device and installation parameters, while the variability range of parameters in the *Z–R* relationship, is linked to the microphysics of the hydrometeors. Many authors tried to provide the parameters of the *Z–R* relationship as a function of the event classification and climatic conditions (e.g., Battan, 1973; Willis and Tattelman, 1989; Tokay et al., 1995; Tokay and Short, 1996; Ulbrich and Atlas, 2002; Chumchean et al., 2008).

Collections of disdrometer data provide local set for the calibration of the *Z–R* parameters at the installation location; with this purpose Rosenfeld and Ulbrich (2003) showed a list of different parameters available in the literature for different locations. They tried to apply the conceptual insights derived from the microphysics theory to identify relationships between the characteristics of these parameter sets and geographic elements, such as the maritime-continental classification and the prevalent precipitation mechanisms.

Eventually, the availability of rain gauge network data makes it possible to design a correction procedure that operates a spatially distributed adaptation of the radar precipitation estimates to ground measurements (e.g., Koistinen and Puhakka, 1981; Krajewski, 1987; Creutin et al., 1988; Velasco-Forero et al., 2009; Sideris et al., 2014). This operation ensure the congruence with ground measurements that often represents a requirement for estimates.

In this study the exploitation of information provided by the low-cost single polarization X-band weather radar, supported by other devices of the monitoring system of the urban area of Palermo, is pursued by means of an operational procedure where several interactions and blending applications exploit sensors data for the retrieval of best precipitation estimates. In particular, the following three modules have been designed and implemented:

- calibration of the radar equation;
- calibration of the *Z–R* relationship;
- correction of radar estimates based on rain gauge network data.

While the radar equation and the *Z–R* relationship calibrations have been both designed on the basis of the disdrometer measurements, the rain gauges correction exploits the availability of data from the rain gauge network.

Each application has been evaluated considering its suitability for both monitoring and hydrological applications.

The disdrometer data have been further employed for the analysis of a 1 year observation period. In particular, the *Z–R* parameters of the events occurred during this period have been assessed. The analysis here performed tries to estimate some reference values for the area, based on meteorological and climatic features, that could provide useful information for specific studies about the spatial variability of the *Z–R* relationship.

In the next section, the monitoring system is described along with details about sensors and their distribution in the territory. Results obtained from different analyses carried out for the exploration of measurements and sensors blending possibilities are presented and discussed in the other sections.