Evaluation of X-band radar technologies within Opera 3 project

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1. Introduction

The emergence of X-band weather radars is a relevant aspect characterizing radar meteorology in the last ten year. Nowadays X-band radars provide an attractive cost-effective solution for many weather radar applications also because of their cost (in terms of purchase, infrastructure set up and maintenance costs) than conventional C- or S-band radars with comparable beam-width resolution. The fundamental objective of OPERA 3 project is to provide a European platform wherein expertise on operationally-oriented weather radar issues is exchanged and holistic management procedures are optimized. An important objective of OPERA is to act to harmonize data and product exchange at the European level. Within the framework of OPERA 3 project, these new radar technologies has been evaluated in a specific task, part of a workpackages about evaluation of new radar technologies.

In Europe, several projects are ongoing that involve installation of new radar systems with extremely different technical characteristics, but using X-band. The main drawback is represented by attenuation due to propagation through precipitation, that determines important errors in radar rainfall estimation obtained from parameters derived from power measurements. The use of dual-polarization techniques in X-band radar systems has provided solutions to mitigate the impact of attenuation. This fact has revived in the recent years the interest of the scientific and the operational communities about these systems, that are now considered a convenient solution for applications such as rainfall measurement over a small watershed, to fill gaps in operational radar network, and, when used in a networked environment, for improving lower atmosphere coverage, and capability to trace and track storm cells in the presence of small scale and high impact cases. An important aspect related to the reduced size of X-band radars is the possibility of implementing them as mobile system. In this way they can be quickly deployed and used to provide adequate coverage of specific areas subjected to emergencies. Among advantages of X-band for dual polarization radar systems we can mention the improved sensitivity of differential phase measurements to precipitation. This sensitivity allows building up reliable algorithms for rainfall estimation based on the use of differential phase shift, a parameter based on phase of radar returns, immune to attenuation caused by propagation, and at some extent to beam blocking (Wang and Chandrasekar 2009). This feature increase usefulness of X-band polarimetric systems in estimating precipitation in mountainous area.

The number of X-band is constantly increasing in Europe, following a worldwide trend. Such systems include very low single parameter, fixed elevation radars, high end dual polarization radars, fixed and mobile radars targeting specific advanced research topics. Finally, some radars are installed to form autonomous X-band radar network, whereas in limited cases, they are mosaicked into national and OPERA European composite. In general, such radars are becoming more and more important in weather services either to improve coverage of national weather radar networks or to be used by organizations operating at regional or metropolitan area scale. In the US, the recent project CASA (Center for Collaborative Adaptive Sensing of the Atmosphere, Mc Laughlin at al, 2009) aimed to deploy an experimental network of small X band polarimetric radars in Oklahoma as a proof of concept of a new paradigm for precipitation sensing based on low cost X-band polarimetric radar with overlapping coverage. In Japan, the NIED (National Research Institute for Earth Science and Disaster Prevention) deployed an experimental network of three X-band polarimetric radars (X-NET) in the Tokyo metropolitan area to improve the coverage of the regular C-band radar network of the Japan Meteo Agency (Maesaka et al. 2011). In Europe since '70 there were several attempts using X-band radar technologies in hail detection (Prodi, 1974, 1976) and later in '90 several experiences with X-band light configuration radar were performed in France (Delrieu and Creutin, 1991, Delrieu, 1997). The progresses in polarimetric recently increased also in Europe the interest in X-band radars, as quantitative precipitation estimations (QPE) appear now possible with the requested accuracy.

In complex terrain the radar beam can experience partial or total blocking. As a consequence, in regions characterized by a complex orography, the coverage of operational C-band networks is often inadequate or even non-existent. This problem often occurs in Europe in the Alpine and Pyrennes areas. This problem can be partially mitigated by resorting to sampling precipitation at higher elevation, determining an increase in the decorrelation between rainfall at ground and precipitation sampled by radar. Coverage gaps typically occur in mountainous basins. Unexpensive X-band radars represents an attractive solution. Due to high spatial (~ 50 m) and temporal resolution (~ 30 sec), the interest of using X-band radar for urban areas hydrology has recently emerged as demonstrated by PATTERN project, in the area of Aukrug near Hamburg, or by Dallas Fort Worth (DFW) Urban Demonstration Network in the US.

A survey of meaningful experiences in Europe and focusing on the operational and technological aspects of weather radars at X-band was conducted between 2010 and 2011. Although X-band weather business is rapidly evolving, this
surveys has allowed to highlights the current status of X-band weather radar form the point of view of the community of operational weather services in Europe. In addition to statics emerging from the survey, a summary of activities aiming at assessing data quality of X-band radar is presented.

2. A survey of existing X-band radar in Europe

In the recent years we have seen a growing interest in X band polarimetric systems for operational applications. Systems with different characteristics and prices are nowadays available from several manufacturers. The number of installations and projects targeting different applications of X-band radar is rapidly growing as well.

Therefore, during past years an extensive survey of existing X-band systems has been performed, considering operational, pre-operational or research X-band radar used in Europe for local purposes or as complement of C-band radar networks. The survey includes only horizontally or volumetric scanning radar (i.e. vertical pointing radar are excluded) managed by meteorological services operating both at national or, hydrological or research institutes. Moreover, both non polarimetric and dual polarization systems have been analyzed.

The figure 1 shows the distribution of X-band radars by country updated at March 2011. Italy and Denmark are the country where X-band technologies have grown faster during past years, followed by France and Germany. Meanwhile in Denmark there is a homogeneous network of Doppler small radar, mainly focused on local weather. In Italy, and also in France and Germany, different type of instruments are installed in different regions. About 33% of overall installations are polarimetric with radome, while 15 radar remaining are non-Doppler and non-polarimetric radars.

Notable for technology development is the Delft FMCW research radar in Delft (NL). Wide spread is declared about maximum useful range that ranges from 40 km to 100 km. Regarding the antenna, some radars exhibit a fan-beam antenna with horizontal resolution of 0.95° and vertical one 20°. Others, using a standard parabolic reflector, declare horizontal and vertical resolution ranging from 1.35° to 4°. Highest installations are located in Swiss, on Klein Matterhorn (Zermatt) at 3,888 m a.s.l. and in Davos at 2,152 m a.s.l.

These new installations are sometimes mobile and related to the support of emergency operations due to natural phenomena allowing radar monitoring, like volcanic ashes (Italy). More frequently, installations are related to research, local or municipality weather services (Denmark, Mt.Vial in France), gap filling (France) or Alpine hydrology (Swiss).

Regarding economic aspects few data has been collected but instruments costs seem to range from 100 kEuro to 500-700 kEuro, depending on systems characteristics, such as polarimetry. Regarding maintenance performance and costs, few informations have been collected; one possible interpretation could be related to the relatively young age of the installations and maintenance problems will be faced during next years.

In spite of the growth of the number of projects employing X-band radars, both as standalone or networked system, an aspect that should be more carefully considered is how or if these new instruments are planned to be integrated with other operational measurements like raingauge ground networks and operational C-band Radar. At the moment, only one X-band radar is delivered operationally to the Opera composite by Italy; soon with the ongoing French RHYTMME project new radars will be included.

Fig. 1 X-band radar in Europe at March 2011.
2. Approaches to data quality

Some result on X-band assessment on data quality come from Arpa Piemonte and MétéoFrance experiences, mainly carried out along the FRAMEA project, Alcotra programme 2003 – 2007, tested polarimetric Doppler X-band radar in Alpine regions, ForeAlps project, Alcotra programme 2003 – 2007, tested also tested low-cost X-band, ant the RHYTMME (Risques Hydro-météorologiques en Territoires de Montagnes et Méditerranéens) project, which is aiming to establish a platform service for a better management of hydrometeorological hazards in this region. The RHYTMME Project aims to deploy a dense network deployment of 4 polarimetric X-band radars over the period 2010 – 2013 (see fig. 2). Whereas the activity in Piemonte was primarily focused intensive investigation of radome attenuation in wet radome conditions, preliminary activities, the RHYTMME project aims to optimize the processing chain for QPE and influence of QPE of data quality. This section presents the current status of the processing chain and discusses the preliminary results of the evaluation of various QPE algorithms.

Concerning radome effects, although thorough investigations on radome effects have been performed at DWD as reported by Frech et al. (2009) using one year of measurements collected by a 12-year old orange-peel radome that was not properly maintained. The impact of radome has been also investigated by Arpa Piemonte, in collaboration with the Colorado State University (Bechini et al. 2010), and a quite brand new polarimetric radar and a relatively new radome (about 2 years old).

An experiment was conducted using the X-band dual-polarization radar of ARPA Piemonte and a laser disdrometer installed besides the ARX radar trailer. The disdrometer, used to retrieve both the rainfall rate and the horizontal radar reflectivity $Z_h$, measured the Drop Size Distribution (DSD) in terms of particle counts, stratified in 22 classes of diameters (0.16 mm to > 8 mm) and 20 classes of velocity ranging from 0.2 m/s to 20 m/s. Although the deviation from Rayleigh scattering was in general small for the light to moderate rainfall intensities considered ($Z_h < 45$ dBZ) the reflectivity has been calculated using an electromagnetic simulation. The rough linearity of the loss with $R^{1/3}$, derived during the experiment over the whole rain rate dynamics (0.05 to 25 mm/h) has been interpreted as an indication of the wetting radome surface (water film formation). In presence of a non wetting radome a sharp transition would be expected corresponding to the change in the water flow from rivulets to laminar. The radome was two years old at the time of these measurements and likely had lost the non wetting original conditions, due to degradation with time. The radome, although originally declared hydrophobic by the manufacturer, clearly lost its hydrophobicity properties with time. This degradation may actually occur over a relatively short period of operation, e.g. several months (Anderson, 1975). In a perspective of a dense X-band radar network, a periodical polishing of the radome surface does not appear practical. So, only two options appear viable:

- to operate the radar without the radome (easier at X-band, due to the reduced dimensions, but still impractical in general for the higher wear and also for the “psychological” aging)
- to adopt a procedure to correct for attenuation effects in real time, taking into consideration also non uniform radome wetting with azimuth and elevation (Bechini et al., 2006), e.g. due to wind direction, will also have to be considered for the implementation of a real-time correction procedure.

Fig. 3 Set up of experiment for radome attenuation assessment at ARPA Piemonte (Bechini, 2010).

Méteo France has presented the current status of development of a polarimetric radar network data processing chain to provide accurate QPE to decision makers in a flooding-prone mountainous region. Results of several Pol-QPE algorithms that have been preliminary tested, which are based on simple $Z$-$R$ relationships and on Kdp, have been summarized. Kdp has shown to be a very good candidate because it is unsensitive to calibration errors and partial beam blocking. A synthetic $Z$-$Kdp$ algorithm, which combines $R$-$Kdp$ relations for intense precipitation and $Z$-$R$ relations corrected for attenuation in the weak rain, has been tested and the one which showed the best score was achieved by a combined algorithm (Kabeche et al. 2011) The next steps will be to enhance the evaluation including more events and testing other polarimetric precipitation estimation algorithms, such as the integrated ZZDR technique by Illingworth and Thompson (2005), the variational approach (Hogan, 2007) and ZPHI (Testud et al. 2000).

Once the optimal algorithm will be determined, the implementation of intelligent compositing rules between X-band radars, allowing for a mitigation of attenuation effects and optimal exploitation of the network will be studied. Maps of
minimum detectable signal will also be produced and used in the compositing rules in order to mitigate situations of severe attenuation/extinction leading to complete misses of precipitation detection by radar.

Also the topic of radome attenuation is considered. In fact, as among Mt. Maurielle and Mt. Vial radars, one has a radome and the other one does not, new perspectives will be studied in the quantitative evaluation of wet radome attenuation on polarimetric measurements.

Fig. 3 Map of the full deployment of the network of 4 X-band polarimetric radars in south France for RHYTMME.

3. Common characteristics of X-band radar for QPE application

Results of the survey conducted in Europe have shown a pervasive adoption of X-band radars for a wide range of applications and objectives. In spite of the different type of X-band radar that are proposed, it seems that for QPE applications, some common solutions have been adopted. So that it is possible to set recommendations concerning X-band radars for QPE applications.

1) Polarimetry

Power measurements at X-band, such as reflectivity factor, are affected by attenuation due to wave propagation through precipitation, even in case of weak precipitation. Studies have shown that iterative methods for reflectivity correction can diverge. Dual polarization radar measurements, in particular differential phase, give chances to mitigate attenuation problems, both estimating attenuation effects in reflectivity or to estimate precipitation intensity in algorithms using differential phase shift that can mitigate impact of drop size distribution variability. Nowadays most of dual polarization radars employ the STAR (simultaneous transmit and receive) scheme that allow reliable estimation of differential phase shift, although presents disadvantages in the differential estimation of differential reflectivity.

2) Antenna resolution

X-band systems allow smaller size antenna antennas with respect to an S- and C- band systems having the same resolution. However, X-band systems with poor horizontal or vertical resolution can present a limitation in the effective range that can be used for QPE. Recommendations for resolution can be different in azimuth and in elevation. In azimuth, at a 30-km distance, an azimuth resolution of 2° corresponds to a width of resolution cell of 1 km. Along the horizontal, this can be acceptable for obtaining rainfall maps with a 1-km resolution, but in vertical the same resolution could not be sufficient to assure quality differential phase shift measurements that are affected by vertical gradients, such as those collected in areas with partial contamination with the melting layer.

3) Radome

Many practical issues (cost limitation of the servo/antenna system, security of operations and protection from severe environmental conditions) suggest to install radome on radar systems to obtain measurements in conditions, such as intense wind gusts, that could hamper the functioning of an antenna non protected by the radome. However, several studies have shown its negative impacts on reflectivity and dual-polarization data quality. Performance of a radome depends on several factors, such as the shape of the radome, actual hydrofobicity of the coating and its size. It has been shown that at X-band, loss due of radome wetting can reach the order of 10 dB in the case of heavy precipitation that is hard to estimate in real time. So it could be preferable operating without radome, provided that radar design adopts proper measures to ensure that antenna can withstand wind gusts and cooling of the systems obtained without the thermal insulation provided by the radome. Anyway, when radome is present, efforts must be spent to devise robust algorithms for reducing radome impact on measurements by operational attenuation corrections using phase measurements, or attenuation estimations derived from co-
located disdrometer or by deriving QPE from differential phase measurements that seems less affected by radome effects.

4) Transmitter/Receiver

State-of-the-art digital receiver should be used. They allow low noise figure (of the order of a few dBs) and linear response of at least 90 dB. In dual polarization operational weather radars, magnetron transmitter are commonly adopted. To define peak power several factors should be taken into accounts. In weather radars it is customary to define sensitivity based on the minimum detectable reflectivity factor at a given where the signal-to-noise ratio at a reference plan is 0 dB. Minimum detectable signal, receiver bandwidth /range resolution and transmitter duty cycle limitation are jointly related and are selected based on a minimum reflectivity detectable at a given distance. In the case of attenuating frequencies, a further margin, statistically determined to ensure that a signal be detectable at a given distance in condition of precipitation induced attenuation should be considered. A further margin to be taken into account is related to the attenuation induced by a wet radome. Finally, the radar system should feature BITE remote control and online calibration tests. Moreover, a solar scan utility should be available for pointing and absolute calibration purposes, especially for mobile installations.

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