High-resolution X-band polarimetric radar Observations during the HyMeX 2012 Special Observation Period in North-East Italian Alpine Region: Evaluating hydrologic impacts

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(Dated: 18 July 2014)

1 Introduction

Oftentimes, storms developing in mountainous regions are affected by low level orographic enhancement of precipitation that affects both the small scale variability and intensity of rain rates creating a great challenge to QPE from remote sensing (both operational weather radar networks and meteorological satellites) platforms. For ground radars in particular monitoring of precipitation at long ranges is associated with critical detection issues including partial, or total, beam blockage of the lower beam elevations or with the overshooting of low-level convection signatures by the upper elevation sweeps, which leads to significant range dependent errors in precipitation estimation (White et al., 2003). In addition, melting snow in widespread storm systems that typically result in high accumulations from persistent stratiform-type surface rainfall may substantially increase the threat of localized flash floods in complex terrain basins (Smith et al., 2005).

Current operational rainfall monitoring systems based on national weather radar networks operating on the basis of long-range coverage do not provide sufficient measurements to support accurate estimations of precipitation variability especially in mountainous basins (Maddox et al. 2002). Studies have also shown that precipitation estimation from conventional long-range weather radar observations are affected by significant systematic and random error components associated with a host of sources ranging from the variability in the relationship of reflectivity-to-rainfall inversion to beam geometry and elevation issues including the rain-path attenuation of signal power, the vertical precipitation structure affecting higher elevation angles and longer ranges and the partial or total beam occlusion affecting lower elevation beams (e.g., Zawadzki, 1984; Kitchen and Jackson, 1993).

Current research on X-band rainfall measurements (Anagnostou et al. 2009, 2010; and Nikolopoulos et al. 2014) shows that locally deployed high-resolution dual-polarization mobile systems can achieve higher resolution rain rate estimations than the lower frequency (C-band and S-band) operational radar systems, which can be used to fill in spatial coverage gaps of the high-power C-band or S-band operational weather radar systems in rainfall observations over small scale mountainous basins, which is one of the critical issues for advancing warning systems of hydrological hazards (flash floods, landslides, debris flow, etc.).

The overall objective of this work is to investigate the potential benefits from using a locally deployed X-band dual-polarization radar for hydrometeorological and hydrological studies in mountainous basins. In this paper we present the results of an experimental study conducted over at a mountainous region of the Italia Alps aimed to evaluate the use of precipitation observations from a locally-deployed high-resolution X-band dual-polarization radar for quantification of rainfall variability at high spatial and temporal scale over a small mountainous basin and its application in flood modeling.

2 Study area

The area of study is located in the northeastern part of Upper Adige riven basin (northeast Italy). Specifically an X-band polarimetric (XPOL) mobile radar from NOA (National Observatory of Athens) was deployed approximately 10km southeast from the outlet of Mazia and Gadria basins (Fig.1). The experiment lasted approximately 3 months (Aug-Oct 2012). During that period, precipitation data were collected from XPOL and a large number of in-situ sensors provided from NOA, NASA, EURAC and the autonomous Province of Bolzano. Those in situ sensors include rain gauges and two different types of disdrometers (i.e., one 2D-video and one Parsivel). Furthermore, rainfall estimates from two operational C-band radars (namely Valluga and Swiss) covering the region were available but only for few storm cases.

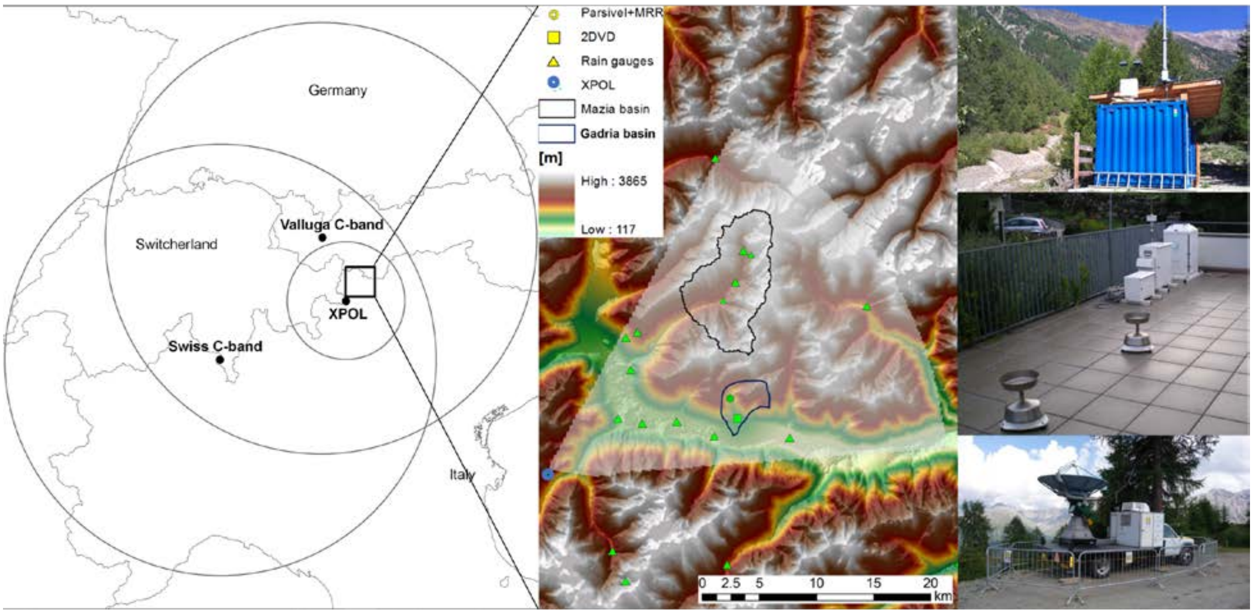

Figure 1: The topography of the experimental area showing the coverage of the XPOL radar encompassing two experimental basins, and the various in situ instruments, and finally the coverage of the two operational network radars. Pictures from the deployed sensors are also shown (lower right is the XPOL radar, middle are two NOA gauges and the two-video disdrometer and top is the Parsivel disdrometer and MRR from NASA)

3 Methodology and Results

The methodology followed in this study includes a) comparison of rainfall estimates between XPOL and the operational C-band radars and b) hydrologic evaluation of radar-rainfall estimates (both X-band C-band) in terms of runoff simulations. Specifically, rain estimates from XPOL and the C-band radars were compared against the in-situ observations. Then radar-rainfall estimates were used to simulate runoff response at the outlet of Mazia basin and results were compared against the gauge-based simulations which serve as the reference rainfall. XPOL rainfall estimates were obtained after correcting for atmospheric and rain-path attenuation and according to a new microphysical algorithm, which are discussed in recent publications by Kalogiros et al. (2013, 2014) and Anagnostou et al (2012). In addition to the precipitation data, discharge observations were available for three different locations at the Mazia basin, which are used to verify hydrologic simulations.

Table 1 presents the main rain events and availability of instruments during the experimental period. The intensity of the events was moderate and no flash floods were observed in the experimental area, but according to flow data there was adequate streamflow in the catchments to support flood modeling.

Table 1: Selected rain events recorded from most sensors during the experiment

Time period (UTC)	Total rain (mm)	Available observations
05/08/12 11:00 - 05/08/12 17:00	10	Rain gauges (all 4 sites), 2DVD, Parsivel, XPol, Valluga
10/08/12 07:00 - 10/08/12 16:00	9	Rain gauges (all 4 sites), 2DVD, Parsivel, XPol, Valluga
21/08/12 22:00 - 21/08/12 24:00	7	Rain gauges (all 4 sites), Parsivel, XPol
25/08/12 16:00 - 25/08/12 24:00	22	Rain gauges (all 4 sites), Parsivel, XPol, Swiss Radar Network
30/08/12 10:00 - 01/09/12 14:00	39	Rain gauges (all 4 sites), Parsivel
05/09/12 12:30 - 05/09/12 23:00	8	Rain gauges (all 4 sites), 2DVD, Parsivel, XPol
10/09/12 08:00 - 12/09/12 21:00	13	Rain gauges (all 4 sites), 2DVD, Parsivel, MRR, XPol, Valluga
24/09/12 07:00 - 27/09/12 21:30	29	Rain gauges (all 4 sites), 2DVD, Parsivel, MRR, XPol, Valluga
29/09/12 07:00 - 30/09/12 06:30	11	Rain gauges (all 4 sites), 2DVD, Parsivel, MRR, XPol, Valluga
01/10/12 10:00 - 02/10/12 02:30	9	Rain gauges (all 4 sites), 2DVD, Parsivel, MRR, XPol
09/10/12 01:30 - 10/10/12 18:30	11	Rain gauges (all 4 sites), 2DVD, Parsivel, MRR
16/10/12 06:30 - 16/10/12 19:00	7	Rain gauges (all 4 sites), Parsivel, MRR

3.1 Radar calibration and validation

The calibration of XPol radar echo signal (horizontal and differential reflectivity) is important for the correct application of the XPol radar algorithms that are presented in this report. This calibration can be assessed using reference radar parameters (reflectivity and differential reflectivity) determined using scattering (T-matrix) routines applied on the drop side distribution (DSD) measurements from the 2DVD and Parsivel disdrometers. The disdrometer measurements were validated using the raingauge rainfall data prior to using them in evaluating the radar biases. Figure 2 shows time series (upper two panels) of the rainfall rate (in mmh^{-1}) and cumulative (lower two panels) rainfall (in mm) plots from the disdrometers and the corresponding rain gauges (every minute) deployed next to each of the disdrometers. The disdrometers agreed well with rain gauges in terms of both temporal variations of rainfall (time series) and the accumulated rain during the event.

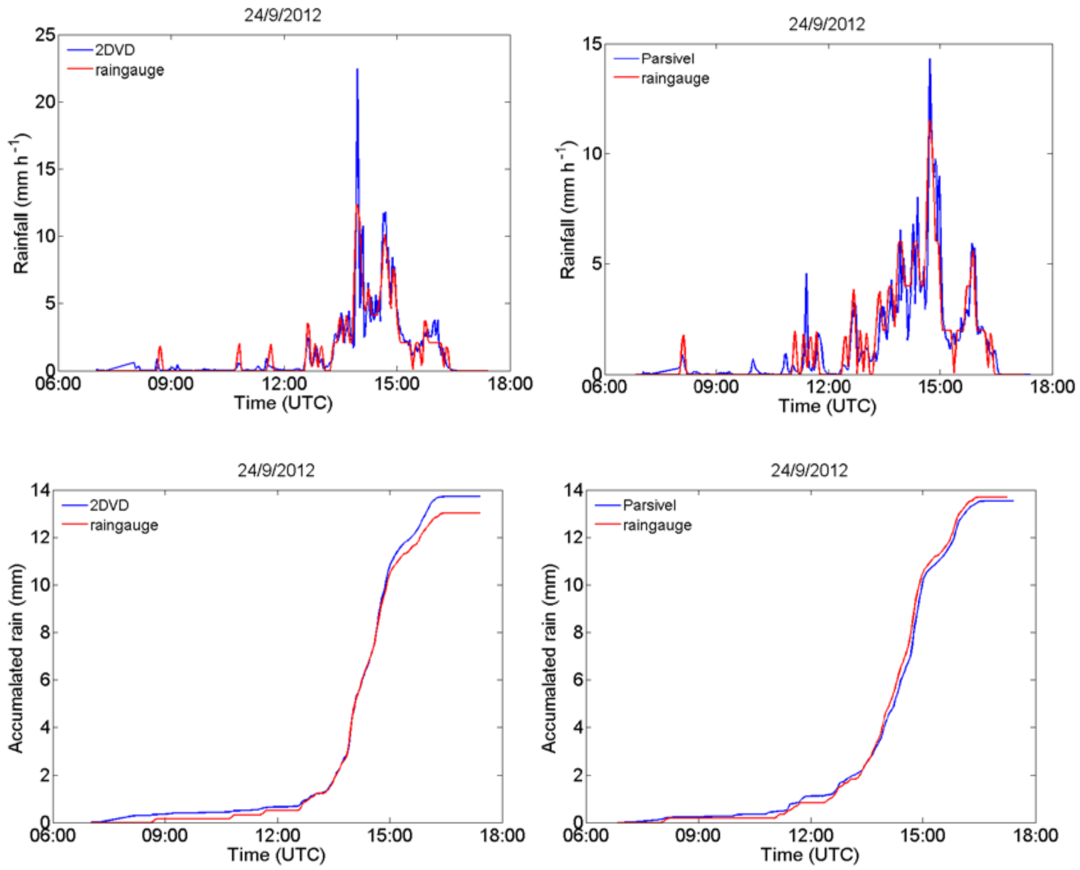

Figure 2: Time series of rainfall rate and accumulated rain form the two disdrometers (2DVD and Parsivel) and nearby rain gauges during the rain event of 24/9/2012

Figure 3 shows scatter plots of the rain-path attenuation corrected XPOL radar horizontal (Z_{hR}) and differential (Z_{drR}) reflectivity and the corresponding (Z_{hD} and Z_{drD}) disdrometer (2DVD and Parsivel) reflectivities.

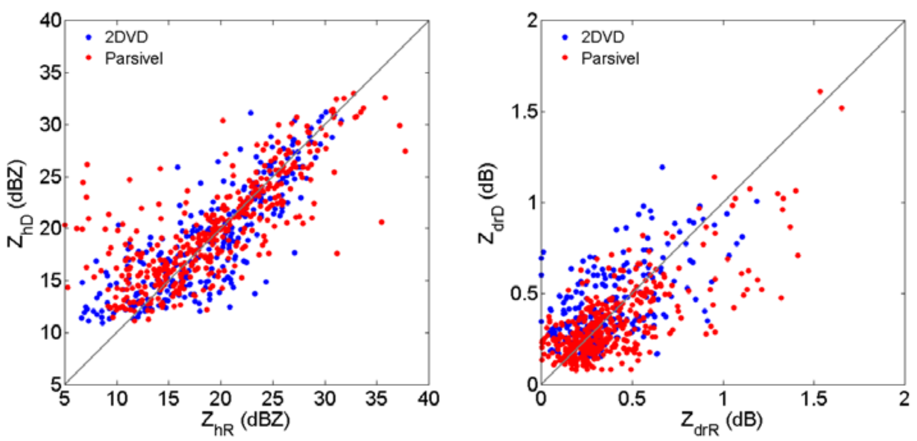

Figure 3: Scatter plots between the radar reflectivity Z_{hR} and differential reflectivity Z_{drR} at the position of the disdrometer (0.5° elevation angle of the radar antenna) and the corresponding reflectivity (Z_{hD} and Z_{drD}) estimated from the disdrometers

The lowest antenna elevation (0.5°) was used because XPOL data from this elevation are closer in altitude to the disdrometers and there was no beam blockage or ground clutter effects affecting measurements at these radar rays. The bias, which was subsequently removed from the radar data, was 3.5 and 3.7 dB for horizontal and differential reflectivity, respectively. These values are close to the calibration biases estimated from previous experiment with XPol radar and disdrometers. The correlation coefficient of radar estimates compared to both disdrometers (2DVD and Parsivel) is about 0.80 and 0.65 for horizontal and differential reflectivity, respectively, and the normalized error (after removing the corresponding biases) is less than 3% for both reflectivity types.

3.2 Statistical evaluation of radar data

The statistical metrics for the evaluation of the algorithms include: (1) the correlation; (2) the conditional bias ratio, which is defined as the sum of radar estimate versus reference values, and the (3) unconditional bias ratio. All the presented statistical analysis is computed for both the reference and the radar estimates in hourly values and presented for in-situ validation site in high (inside the Mazia basin) and low (outside and below the Mazia basin) elevation sites. The XPOL estimates obtained at two different spatial resolutions (i.e., 200x200 meters and 1x1 km) in order to show any potential spatial aggregation effect compare to the large operational radar network (i.e. the Austrian and the Swiss). Finally, for the calculation of the statistical metrics, in each hourly time instance all the different collocated ground validation sites included.

Table 2 summarizes the above mentioned statistical metrics where it is demonstrated that the XPOL rainfall estimates outperform the operational network for all cases (i.e. the different spatial aggregations and in situ elevation sites). We notice for all the selected dates high correlations (i.e. between 0.84 to 0.99 for low elevation and 0.70 to 0.99 for high elevation in situ sites). On the other hand the operational radars show moderate correlations (i.e. between 0.61 to 0.95 in low elevation and 0.48 to 0.95 to high elevations in situ elevation sites). Results for the conditional (i.e. for hourly reference rainfall greater the 0.1 mmh-1) and unconditional (i.e. total) bias ratio exhibit the same pattern in performance of XPol vs C-band radar. Results do not reveal any significant effect on the increase of the spatial resolution from 200 to 1000m. In general, we notice better statistical results when we compare the XPOL rainfall estimates with the high elevation in situ validation sites, with high correlations (0.70 – 0.99) and conditional and unconditional biases that varies between 0.53 to a maximum value of 1.21.

Table 2: statistical evaluation of the radar rainfall estimations versus the different ground validation in situ sites

	Correlation			**Conditional Bias**			**Unconditional Bias**		
Date\Radar	**C-bands**	**XPOL (200 m)**	**XPOL (1000 m)**	**C-bands**	**XPOL (200 m)**	**XPOL (1000 m)**	**C-bands**	**XPOL (200 m)**	**XPOL (1000 m)**
06/08	0.95 (0.95)	0.86 (0.99)	0.85 (0.99)	0.43 (0.69)	0.61 (2.33)	0.63 (2.40)	0.39 (0.44)	0.55 (0.94)	0.57 (0.97)
25/08	0.70 (0.78)	0.89 (0.84)	0.90 (0.84)	0.25 (0.68)	0.78 (1.47)	0.80 (1.45)	0.24 (0.43)	0.77 (0.80)	0.80 (0.79)
11 – 12/09	0.81 (0.79)	0.70 (0.91)	0.72 (0.91)	0.23 (0.35)	1.18 (2.08)	1.25 (2.07)	0.24 (0.18)	1.14 (1.03)	1.21 (1.06)
24/09	0.78 (0.77)	0.99 (0.99)	0.99 (0.99)	0.28 (0.49)	0.90 (1.49)	0.88 (1.47)	0.27 (0.29)	0.88 (0.96)	0.89 (0.93)
29/09	0.48 (0.61)	0.81 (0.95)	0.81 (0.95)	0.21 (0.47)	0.57 (1.16)	0.54 (1.15)	0.20 (0.30)	0.53 (0.61)	0.53 (0.60)

Figure 4 shows scatter plots of the hourly radar rainfall (mm) estimation of XPOL and C-band radar against the low and high elevation in situ validation observations. It is very interesting to note that the XPOL rainfall estimation is almost unbiased in moderate to high rainfalls (i.e. >2 mm). We also note that the XPOL rainfall estimation overestimates compared to low in situ validation site rainfall observations

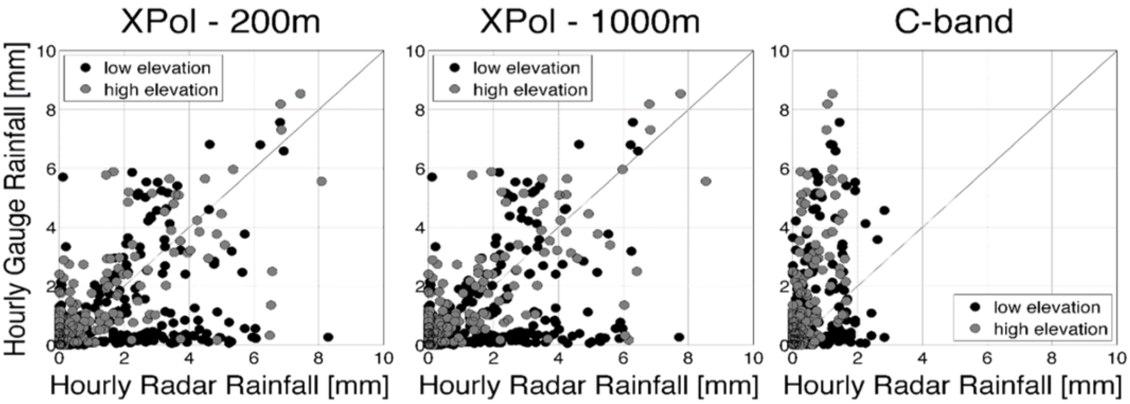

Figure 4: Scatter plots between the hourly rainfall estimation of XPOL and the large operational network radars versus the ground validation in situ sites separated in low elevations and high elevations (inside the Mazia basin)

3.3 Analysis of rainfall spatial pattern

In this section, evaluation of the rain algorithms is performed qualitatively with a visual interpretation of case studies, which include comparisons of rain accumulation maps of the selected rain events. Figures 5 and 6 are used to compare the spatial differences of the two radar rainfall estimates. As we notice, in most of the presented cases and with the help of the bulk statistics presented in Table 3, the C-band radar rainfall estimates are consistently underestimating both rainfall magnitude and variability.

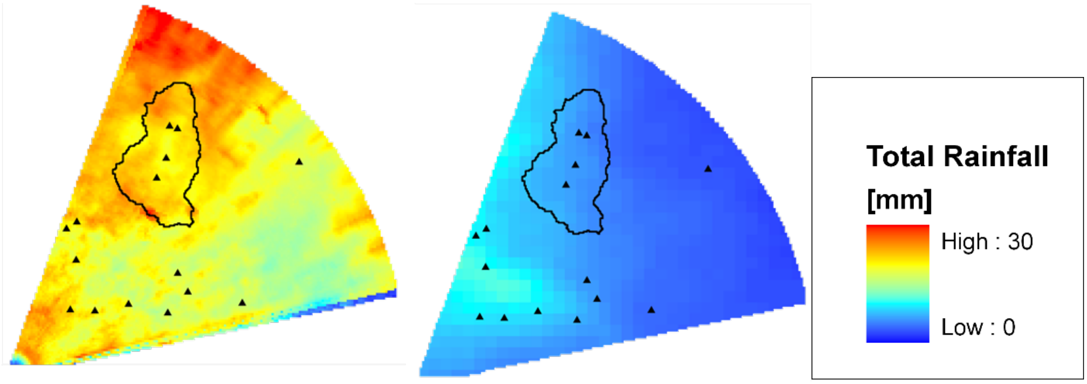

Figure 5: Accumulation plots (during the 25/8) of Swiss network operation radar estimates (on the right panel) and XPOL estimates (on the left panel) showing the large underestimation of the C-band radar

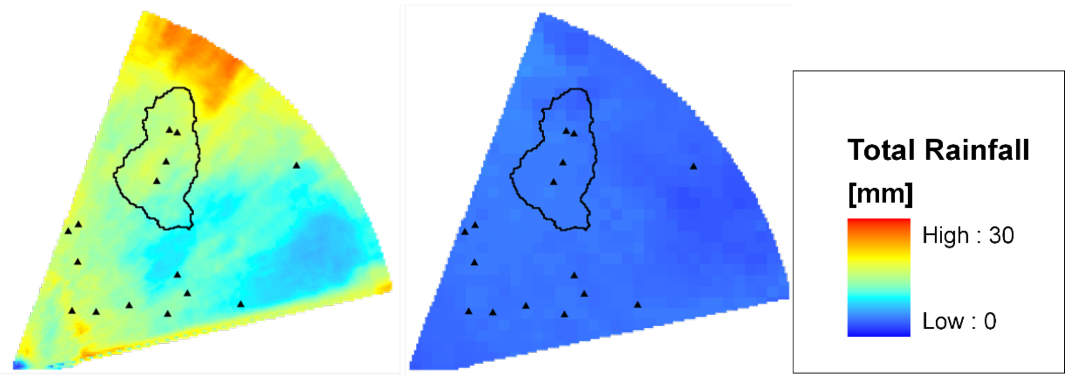

Figure 6: Similar to Figure 5, but for the 24/9 rain event showing the Austrian (i.e. Valluga) network operation radar estimates (on the right panel) and on the left panel the XPOL estimates

4 Hydrological evaluation of radar rainfall estimates

Runoff simulations were performed for the Mazia basin for which discharge observations were available at three different locations (Fig. 7). The drainage area at the three different points is 11.4, 19.1 and 61.9 – km^2, respectively. The basin – average precipitation (in mm) time series provided from the raingauges and the discharge (in m^3s^{-1}) time series derived from the USG and WG1 are shown in Fig. 8. Two high flow peaks during 21 and 25 of August, caused by relatively intense rainfall events (i.e. > 10 mm), correspond to the two main flood episodes that hydrologic analysis is based on. The hydrological model used to simulate runoff at the outlet of Mazia basin is the ARFFS (Adige River Flood Forecasting System).

Table 3: total average precipitation and correlation of the XPOL and the operational network weather radar estimates within the Mazia basin showing the large underestimation of the low-resolution operational weather radars compare to the high-resolution rainfall estimates

25-08 / 24-09	Total basin-average precipitation (mm)	Correlation
Gauge	24.2/18.5	-
XPol – 200m	23.9/14.8	0.85/0.99
XPol – 1000m	23.2/14.4	0.85/0.99
C-bands	06.0/04.5	0.86/0.92

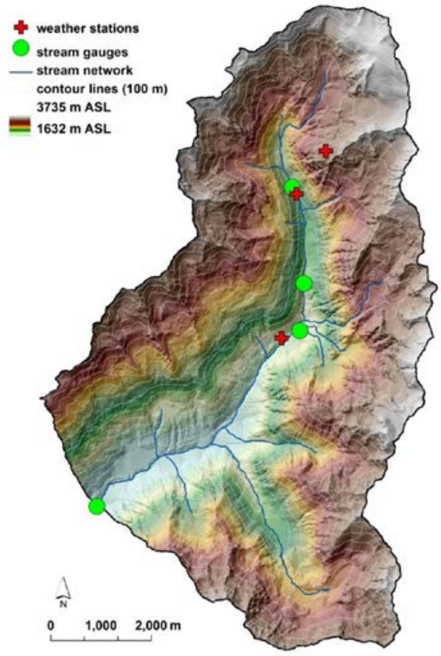

Figure7: Topographic map of Mazia basin showing also the locations of discharge and meteorological stations located within the basin.

ARFFS runs operationally by the Hydrographic Office of the Autonomous Province of Bolzano and is a continuous conceptual hydrological model (Norbiato et al. 2009; Norbiato and Borga, 2008), which is based on the PDM rainfall-runoff model (Moore, 2007) coupled with a snow model (Cazorzi and Dalla Fontana, 1996). The model is forced with hourly X-band, C-band and raingauge precipitation observations and the temperature data provided from the meteorological stations. Radar-based simulations are compared against gauge-based (used as reference) to evaluate the potential of radar sources for simulating flood response.

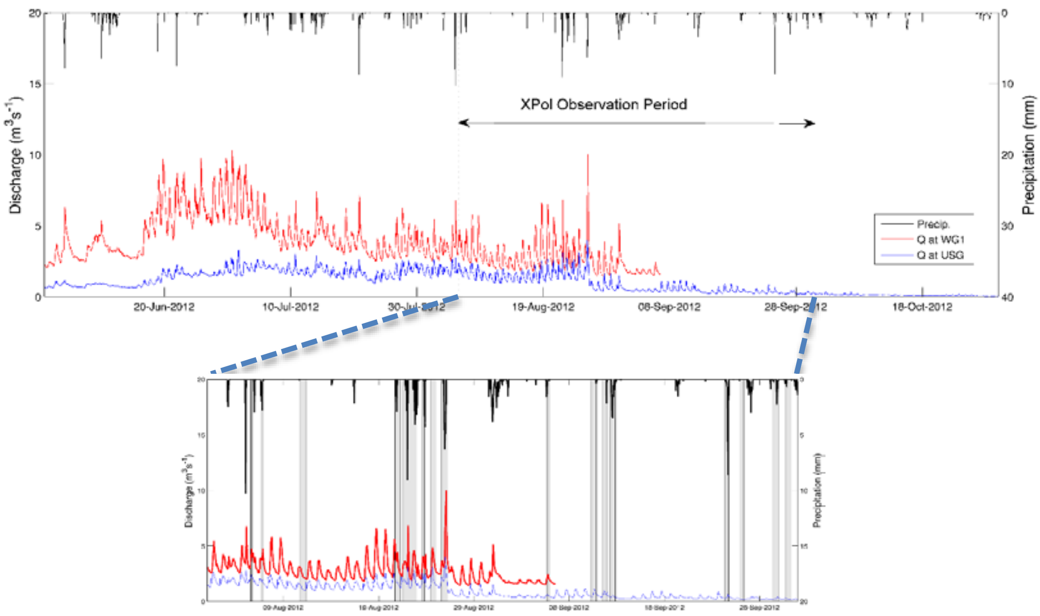

Figure 8: Time series of basin – averaged precipitation provided from the raingauges and stream flow derived from the USG and WG1 gauges. Grey are corresponds to the exact period of XPOL data records

4.1 Analysis of simulation results

Results for the hydrologic evaluation of radar rainfall estimates for the events during 21 and 25 Aug., 2012 are summarized in Fig. 9 below.

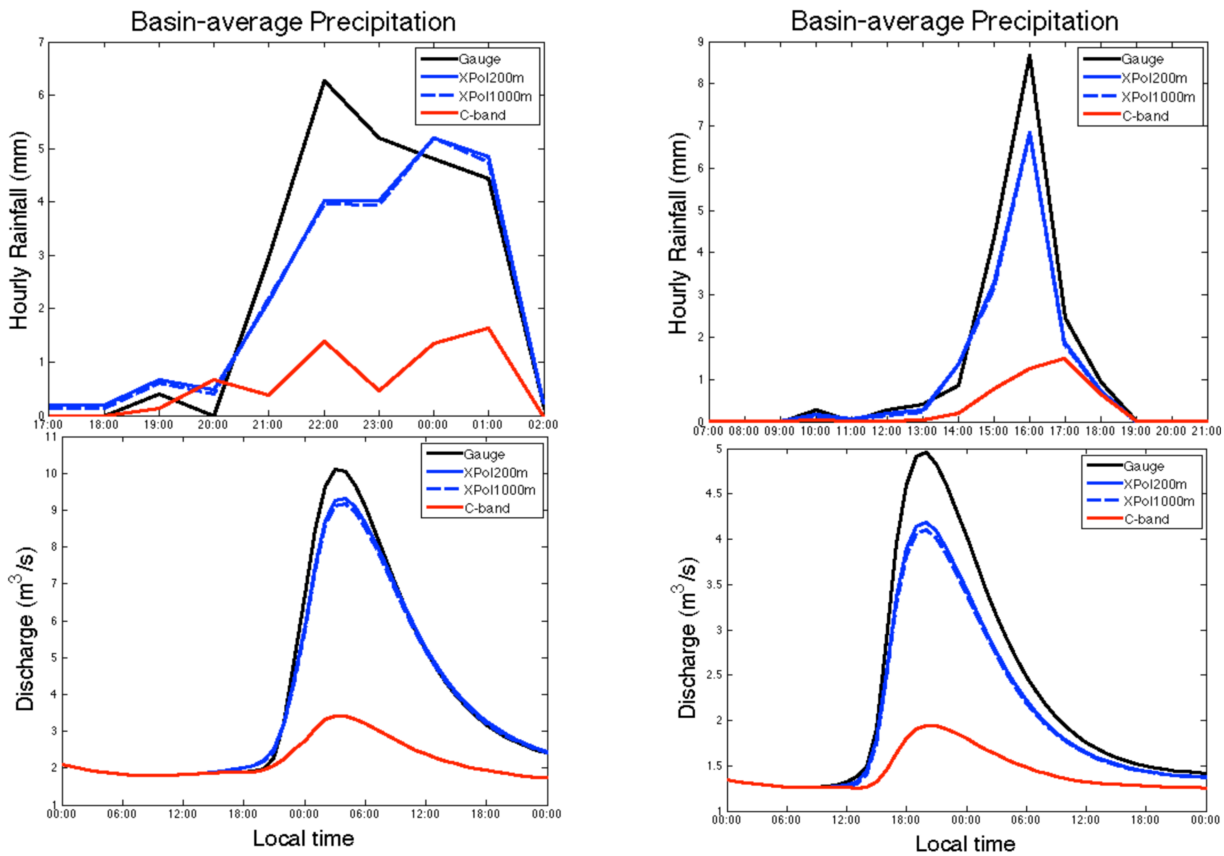

Figure 9: Time series of basin – averaged precipitation and simulated discharge at Mazia outlet (WG1) during 25 Aug(left) and 21 Aug(right), according to gauges(black), XPol-200m(blue), XPol-1km(blue dotted) and C-band(red) estimates

As is shown from the results, runoff simulations based on XPol estimates are very close to the reference (gauge-based simulations) while the simulations obtained from the severely biased C-band estimates have resulted in a tremendously underestimated runoff response with a corresponding hydrograph that shows merely a peak in flow. Specifically, as it is shown in Table 4, relative error for XPol based simulations are associated with a relative error in peak less than 10 and 18% for 25 and 21 Aug respectively while the C-band resulted in 66 and 61% error. In total runoff XPol was associated with <10.5% error in all cases while C-band resulted in error between 35-44%.

Table 4: Relative error in peak and total volume of runoff and error in time to peak for the radar-based simulations examined

25-08 / 24-09	Error in peak (%)	Error in volume (%)	Error in time to peak (h)
XPol – 200m	7.7/15.6	2.3/9.3	1/0
XPol – 1000m	9.1/17.2	3.6/10.4	1/0
C-band	66.1/60.7	43.9/35.9	0/0

These results highlight the tremendous impact that underestimation of the C-band radar may have on the simulations of flood response and further highlight the great potential associated with the X-band polarimetric observations.

5 Conclusions

In this report we presented the advantages from locally deployed high-resolution X-band dual-polarization mobile weather radar (XPOL), relative to operational C-band radars, in terms of measuring rainfall over mountainous basins and associated impacts in simulating runoff in small-scale basins. The National Observatory of Athens XPOL radar data were corrected for effects due to rain-path attenuation and the complex terrain (beam blockage, VPR correction). For accurate calibration of radar reflectivity as well as to develop polarimetric rainfall algorithms we used high quality measurements from two disdrometers located at a site close to the radar with no intermediate obstacles. For beam blockage estimation high resolution terrain information and a three dimensional model of the radar beam was applied. This information is significant to exclude from further processing highly occluded areas or to correct reflectivity from areas with minor occlusion (e.g. 3dB reduction of ZH). The choice of XPOL rainfall algorithm is also a crucial step for accurate rainfall estimation. Polarimetric algorithms (i.e. formulae combining polarimetric radar products) are more accurate and can be applied under different rain types and in different geographical areas because less assumptions are made in their development.

Five rain events were selected to study in this work. The intensity of the events were moderate to low and no flash floods were observed in the experimental area, but according to the discharge observations there were adequate streamflow in the catchments. For the evaluation of radar rainfall estimates we select fifteen (15) different in situ validation sites, each one located in different elevations (m). The high-resolution XPOL rainfall estimations spatial aggregated to high (200x200 meters) and to low (1000x1000 meters) resolutions.

The comparison of the two different XPOL's spatial aggregation estimates with the in situ validation sites in both high (inside the Mazia basin) and low (bellow the Mazia basin) show high correlations (between 0.70 to 0.99). Also, the bias ratio for conditional (i.e., for in situ rainfall observation greater than 0.1 mmh-1) and unconditional (i.e., total) varies around 21 – 53%. We should note here that there is not any effect in the estimation due to lowering the spatial resolution. The bulk statistics show better comparisons with the in situ validation sites within the Mazia basin. Finally, we notice that the XPOL rainfall estimation algorithm is almost unbiased to higher rainfalls (i.e. > 2 mm). On the other hand, both the Valluga and Swiss radar network rainfall estimates comparisons with the validation sites show low bulk statistics in both correlation and biases compared to the XPOL estimates.

Visual interpretation of two case studies (i.e. 25/08 and 24/09), which include comparisons of rain accumulation maps of the selected rain events, which are also used to compare any spatial differences of the two radar rainfall estimates, show that the two C-band radar (Valluga and Swiss) area-average rainfall estimates of the Mazia basin are consistently underestimating rainfall by ~75%. On the other hand, the XPOL estimates show almost 1% bias for the 25/08 (a more convective type of storm) and ~20% for the 24/09 (a more stratiform).

Discharge observations were available at three different locations. The drainage area at the three different points is 11.4, 19.1 and 61.9 – km2, respectively. Two high flow peaks during 21 and 25 of August, caused by relatively intense rainfall events (i.e. > 10 mm), correspond to the two main flood episodes that hydrologic analysis is based on. As it is shown from the results, runoff simulations based on XPol estimates are very close to the reference (gauge-based simulations) while the simulations obtained from the severely biased C-band estimates have resulted in a tremendously underestimated runoff response with a corresponding hydrograph that shows merely a peak in flow. These results highlight the tremendous impact that underestimation of the C-band radar may have on the simulations of flood response and further highlight the great potential associated with the X-band polarimetric observations.

The findings from this study demonstrate the importance of using locally-deployed X-band radar units in quantifying precipitation at high spatio-temporal resolution over complex terrain basins. It remains to be demonstrated as to how significant is this improvement in terms of rainfall product resolution and accuracy on the simulation of floods for a range of basin scales and watershed characteristics. Another limitation of this study is the number of storm cases. Although the sample size associated with the five storms used to determine the error statistics is large enough to generate statistics (mainly due to the number of gauges), we lack a comprehensive evaluation in terms of different storm types, rainfall intensities and precipitation microphysics. We expected a new field experiment to be planned for the same region in the Spring-Fall 2014 to enrich the database to further support the error analysis presented in this study. Finally, the data collected in this study can be used to quantify the improvement in terms of flood prediction achieved by locally-deployed low-power X-band radar relative to measurements from standard long-range operational (C-band) systems.

Acknowledgement

This work is funded under the action "Support of Postdoctoral Researchers" under the operational programme education and lifelong learning with beneficiary the General Secretariat of Research and Technology co-financed by the European Union and the Greek state. The authors would like also to thank, Dr. Ioannis Sideris for the Swiss Radar Network radar rainfall observations, provided from the MeteoSwiss and Dr. Ulrike Tappeiner for the Valluga radar rainfall observations, provide from the University of Innsbruck.

References

Anagnostou, M. N., John Kalogiros, Frank S. Marzano, Emmanouil N. Anagnostou, Mario Montopoli, and Errico Picciotti, 2013: "Performance evaluation of a new dual-polarization microphysical algorithm based on long-term X-band radar and disdrometer observations", Journal of Hydrometeor. Vol. 14, pp. 560 – 576.

Anagnostou, M. N., J. Kalogiros, E. N. Anagnostou, M. Tarolli, A. Papadopoulos, M. Borga, 2010: "Performance evaluation of high-resolution rainfall estimation by X-band dual-polarization radar for flash flood applications in mountainous basin", J. Hydrology, Vol. 394, pp. 4 – 16.

Anagnostou, M. N., J. Kalogiros, E. N. Anagnostou, and A. Papadopoulos, 2009: "Experimental results on rainfall estimation in complex terrain with a mobile X-band polarimetric radar", Atmospheric Research, Elsevier Ed., Vol. 94, pp. 579 – 595.

Cazorzi, F., and G. Dalla Fontana, 1996: "Snowmelt modelling by combining air temperature and a distributed radiation index", Journal of Hydrology. Vol. 181(1-4), pp. 169 – 187.

Kalogiros, J., M. N. Anagnostou, E. N. Anagnostou, M. Montopoli, E. Picciotti, and F. S. Marzano, 2014: "Evaluation of a new Polarimetric Algorithm for Rain-Path Attenuation Correction of X-Band Radar Observations Against Disdrometer Data", IEEE Geoscience and Remote Sensing Letters, Vol. 52, pp. 1369 – 1380.

Kalogiros, J., M. N. Anagnostou, E. N. Anagnostou, Mario Montopoli, Errico Picciotti, and F. S. Marzano, 2013: "Correction of Polarimetric Radar Reflectivity Measurements and Rainfall Estimates for Apparent Vertical Profile in Stratiform Rain", J. Appl. Meteor. Climatol. Vol. 52, pp. 1170 – 1186.

Kitchen, M., Jackson, P. M., 1993: "Weather radar performance at long range. Simulated and observed", J. Appl. Meteorol. 32, 975–985.

Moore, R. J., 2007: "The PDM rainfall-runoff model", Hydrol. Earth Syst. Sc., Vol. 11(1), pp. 483 – 499.

Nikolopoulos, E. I., M. N. Anagnostou, J. Kalogiros, E. N. Anagnostou, F. Marra, E. Mair, G. Bertolidi, U. Tappeiner, and M. Borga, 2014: "X-band dual-polarization radar observations as a hydrologic supporting tool in the North East Alpine region", International Weather Radar and Hydrology Symposium, Washington, USA, 7 – 9 April.

Norbiato, D., M. Borga, R. Merz, G. Bloschl, and A. Carton, 2009: "Controls on event runoff coefficients in the eastern Italian Alps", J. Hydrology, Vol. 375, pp. 312 – 325.

Norbiato, D. and M. Borga, 2008: "Analysis of hysteretic behavior of a hillslope- storage kinematic wave model for subsurface flow", Advances in Resources, Vol. 31, pp. 118 – 131.

Smith, J. A., Miller, A. J., Baeck, M. L., Nelson, P. A., Fisher, G. T., Meierdiercks, K. L., 2005: "Extraordinary flood response of a small urban watershed to short-duration convective rainfall", J. Hydrometeorol. 6, 599–617.

White, A. B., Neiman, P. J., Ralph, F. M., Kingsmill, D. E., Persson, P.O.G., 2003: "Coastal orographic rainfall processes observed by radar during the California landfalling jets experiment", J. Hydrometeorol. 4, 264–282.

Zawadzki, I., 1984: "Factors affecting the precision of radar measurements of rain." In: 22nd Conference on Radar Meteorology, American Meteorological Society, pp. 251–256 (Preprints).