*Water* **2010**, *2*, 838-848; doi:10.3390/w2040838

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*water*

**ISSN 2073-4441**
www.mdpi.com/journal/water

*Article*

# Heavy Rainfall Monitoring by Polarimetric C-Band Weather Radars

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*Received: 8 October 2010 / Accepted: 8 November 2010 / Published: 9 November 2010*

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**Abstract:** Piemonte region, in the north-western Italy, is characterized by complex orography and Mediterranean influence that often causes extreme rainfall event, during the warm season. Although the region is monitored by a dense gauge network (more than one gauge per 100 $km^2$), the ground measurements are often inadequate to properly observe intense and highly variable precipitations. Polarimetric weather radars provide a unique way to monitor rainfall over wide areas, with the required spatial detail and temporal resolution. Nevertheless, most European weather radar networks are operating at C-band, which may seriously limit quantitative precipitation estimation in heavy rainfall due to relevant power signal attenuation. Phase measurements, unlike power measurements, are not affected by signal attenuation. For this reason, polarimetric radars, for which the differential phase shift measurements are available, provide an additional way in which to estimate precipitation, which is immune to signal attenuation. In this work differential phase based rainfall estimation techniques are applied to analyze two flash-floods: the first one occurred on the Ligurian Apennines on 16 August 2006 and the second occurred on 13 September 2008, causing rain accumulations above 270 mm in few hours.

**Keywords:** extreme rainfall; polarimetric radar; flash flood; differential phase shift

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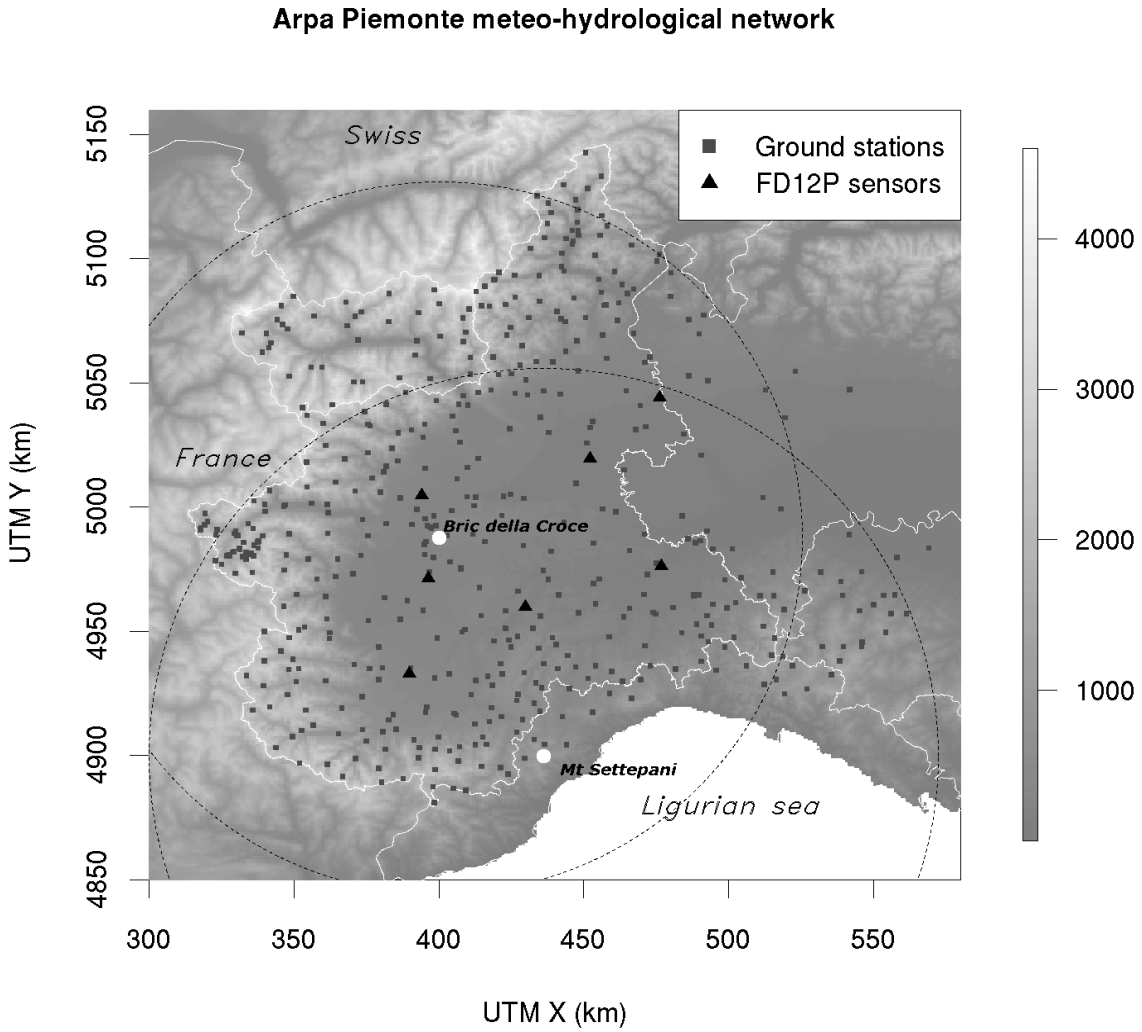
## 1. Introduction

The study area, located in north-western Italy, is characterized by complex orography It is bordered on the north and west side by the Alps, with peaks of around 3,000 meters above sea level. The central part of the Piemonte region is characterized by relatively flat ground and is divided by the Po River that flows in the west-east direction. To the south, the Apennines chain extends from Franch in an eastward direction, forming a border between the Po valley and the Ligurian Sea. Both the Mediterranean influence and the complex orography of the area favor precipitation; resulting in heavy rainfall and flash floods during the warm season. Figure 1 shows study area and meteorological network managed by Arpa Piemonte, composed by ground stations, Vaisala automatic weather sensors (FD12P) and two C-band Doppler polarimetric radar.

**Figure 1.** The study area: the Piemonte region. Circle shows radar maximum unambiguous range, points are ground weather station, triangles represent automatic weather sensors. Altitude is expressed in meters above sea level.




Rain-gauge networks often miss localized and intensify precipitation [1]. Weather radars give a unique way to monitor rainfall over wide areas, with a high spatial detail and temporal resolution,

provided that signal is above the minimum detectable signal. Nevertheless, most European weather radar networks are operating at C-band (a wavelength of about 5 cm), which may seriously limit quantitative precipitation estimation in heavy rainfall, due to relevant power signal attenuation [2].

Phase measurements, unlike power measurements, are not affected by signal attenuation or hail contamination. In addition, the increasing of rain drops with increasing rainfall intensity causes horizontally polarized radar waves to suffer a higher propagation phase shift with respect to the vertical polarized waves [3]. For this reason, polarimetric radars, for which the differential phase shift measurements (the difference between phase shift at horizontal and vertical polarization) are available, provide an additional way to estimate precipitation, which is immune to signal attenuation.

In this work polarimetry-based rainfall estimation techniques are applied to two relevant flash-flood cases: the first one occurred on the Ligurian Apennines on 16 August 2006 and the second one occurred on 13 September 2008 in the area of the Torino international airport Caselle, causing rain accumulation above 270 mm in few hours.

## 2. Data

The region is monitored by a dense ground network, composed of over 400 gauges, two C-Band polarimetric and Doppler radars, near Torino in Bric della Croce at 770 m.s.l. and near Savona in Monte Settepani over the Apennines at 1,400 m a.s.l. (Figure 1). In the present work, reflectivity and differential phase shift reflectivity raw data, measured by both the Bric della Croce radar and Mote Settepani, have been used. The primary radar scan with short pulse (0.5 μs) is composed of 11 elevations, a maximum scan range up to 125 km for Bric della Croce and 136 km for Monte Settepani and 300 m range bin resolution. The complete scan was repeated every 10 minutes. The main technical characteristics of Bric della Croce and Monte Settepani radar are reported in Table 1.

**Table 1.** Main Arpa Piemonte radar characteristics.

| | **Bric della Croce** | **Monte Settepani** |
|---|---|---|
| Model | Meteor 400C | GPM250C |
| C-band frequency: | 5,640 MHz | 5,626 MHz |
| Antenna 3-B beam-width: | 1 ° | 1 ° |
| Antenna rotating speed: | 6 °to 36 °$sec^{-1}$ | 6 °to 36 °$sec^{-1}$ |
| Transmitter type | Magnetron | Klystron |
| Peak power: | 250 kw | 250 kw |
| Pulse duration: | 1–2 μs | 0.5–1.5–3 μs |
| Dual-polar: | H and V alternates (simultaneous since May 2008) | H and V alternates |

Polarimetric radar measurements were de-cluttered by fuzzy logic algorithm [4,5] and interpolated on a 500 m resolution UTM (Universal Transverse Mercator)European Datum 1950 Cartesian grid (UTM ED50).

## 3. Rainfall Estimation Algorithms

Remote measurement of rain (R) has a considerable practical interest. For many years radar meteorologists have attempted to find a useful formula that relates R to the reflectivity factor Z [2]. With conventional single polarization radar in each range bin the rainfall rate *R* is derived from the radar reflectivity *Z* using an univocal Z-R relationship:

$$R = a\, Z^b \quad (1)$$

Where a and b are constant. Moreover to prevent significant overestimates of rainfall rate, due to hail contamination, values of Z are capped to 55 dBZ.

There is no unique relationship between Z and R, therefore, rainfall estimation based on (1) will lead to errors. It has become clear that the errors in R are not only due to changes in drop size distribution (DSD), but there is a variety of factors that can cause systematic, random and range dependent errors. A short list of factors affecting the accuracy of rainfall derived from radar measurements is shown below [6]:

1. High variability of raindrop size distribution which determines the Z-R relationship.
2. Changes in the vertical reflectivity profile.
3. Bright band effects caused by scattering of radar waves by ice particles present in the higher levels of some clouds.
4. False echo caused by anomalous propagation of radar waves.
5. Miscalibration of radar electronic instruments.
6. Erroneous measurements of the received power.
7. Atmospheric processes between the level of the measurement cell and the ground.

It is well-known that *Z* does not only depend on *R*, but also on the characteristics of raindrop size distribution, and in particular on its media diameter $D_0$, which is subject to large variability. To overcome these difficulties, polarization diversity techniques that probe the medium both at horizontal (H) and vertical (V) polarizations have been developed [3].

The most commonly used polarimetric radar measurements in rainfall estimation are the reflectivity factor, usually at horizontal polarization ($Z_h$), differential reflectivity ($Z_{dr}$) and specific differential propagation phase ($K_{DP}$). Based on the above three measurements, a number of algorithms have been derived in the literature to estimate rainfall [3]. These algorithms have been derived assuming a particular shape-size relation for raindrops (DSD).

At C-band the specific differential phase shift $K_{DP}$ is almost linearly related to the rainfall rate. This makes it an extremely useful estimator, especially for high rainfall rates, since phase measurements are not affected by attenuation. The critical aspect of this method relies on the calculation of $K_{DP}$ from differential phase shift $\Phi_{DP}$. In fact, $\Phi_{DP}$ is relatively noisy and may be affected by backscattering differential phase $\Phi$. In order to reduce the noise and remove the backscattering $\Phi$ component, the filtering techniques [7] have been applied to the observations.

The algorithm ZPHI [8] uses the differential phase rotation between two distant range gates, on the same ray, to estimate the integrated rain attenuation between these two range gates. This is then introduced in the attenuation correction algorithm [9] to correct for the rain attenuation.

## 4. Case Studies Analysis

In the following section, two flash floods that occurred in north-western Italy are analyzed; comparing radar derived rainfall fields with ground measurements

### *4.1. Flash Flood on 16 August 2006—Ligurian Apennines*

A low pressure trough, centered on north-western Britain, moved southward, merging with another depression present on the bay of Biscay. This configuration conveyed wet South-westerly winds on the Piemonte region. On 16 August 2006, the depression moved south along the Atlantic coast and at the same time an African anticyclone expanded north-eastward, causing an intensification of wet south-westerly winds and heavy precipitations above Ligurian Apennines. The maximum rainfall intensities were observed between 01:00 and 04:00 UTC, when the raingauge at Fiorino, near Genova, registered 270 mm over three hours. A radar rainfall analysis is performed using the following four techniques:

1. $R_{:}$: unadjusted radar rainfall estimates obtained by using Marshall-Palmer Z-R relation [10];
2. $R_{h,adj}$: same Marshall-Palmer Z-R relation as in (1), but applying corrections for occlusion [11] and an iterative adjustment technique for attenuation [12], based on rain-gauge measurements;
3. $R_{ZPHI}$: adjusted radar rainfall estimates, obtained by using differential phase shift to correct for attenuation and by $N_0$* normalization [8];
4. $R_{KDP}$: based on a linear relation between R and $K_{DP}$, with $R_{KDP} = 19.8 \times K_{DP}$ [13].

The four accumulated rainfall fields, over the event, were obtained from the 0.3 °elevation scan.

Figure 2 shows the comparisons between four algorithms and rain gauge. The accumulated precipitation varies markedly depending on the different approaches investigated. $R_h$ algorithm shows low correlation (0.85) and a strong underestimation; the high rainfall accumulation core is almost completely missed in the unadjusted estimate. Estimates $R_{h,adj}$ obtained by using correction for occlusion and attenuation compares favourably with $R_{ZPHI}$. $R_{ZPHI}$ and $R_{KDP}$ reach good value of correlation of 0.95. $R_{KDP}$ for this case of heavy convective precipitation shows little underestimation, as remarked later.

The Figure 3 shows rainfall accumulated during the event (about 9 hours), as estimated by the $K_{DP}$ method, as well as the location of the rain gauges locations. Heavy precipitation interested and area 40 km far from the radar of Monte Settepani in north-West direction. It's worth noting that the flash flood core was missed by ground network.

**Figure 2.** Rainfall accumulation since 00:00 UTC to 09:00 UTC on 16 August 2006 by radar and ground station location estimated by four algorithms.

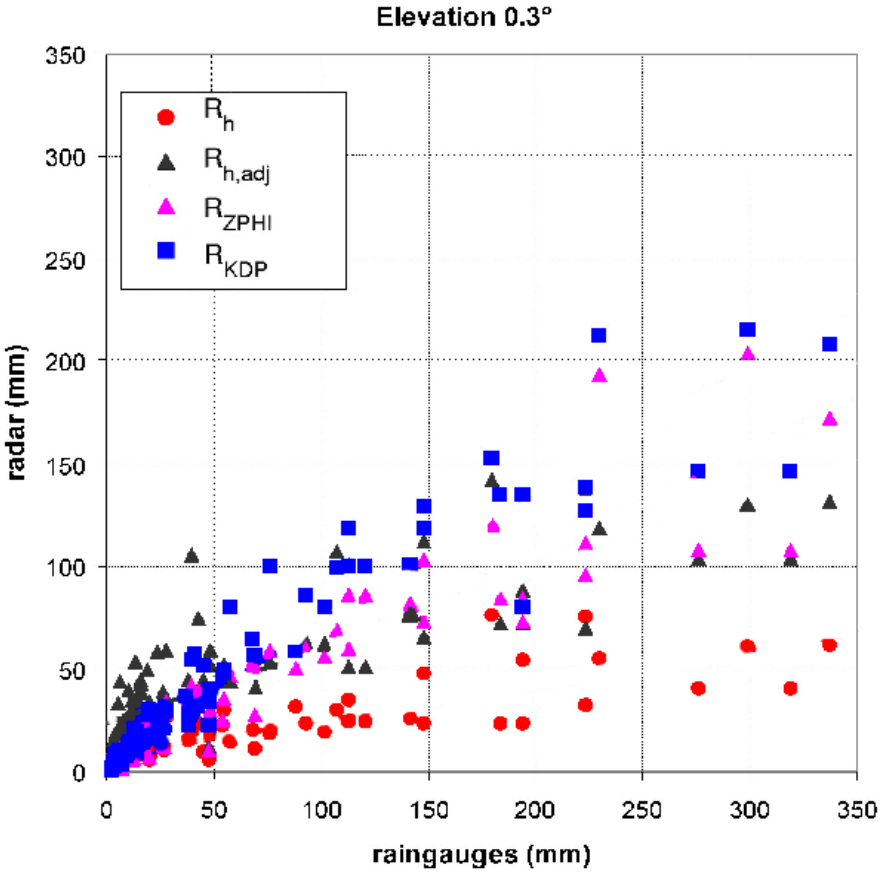
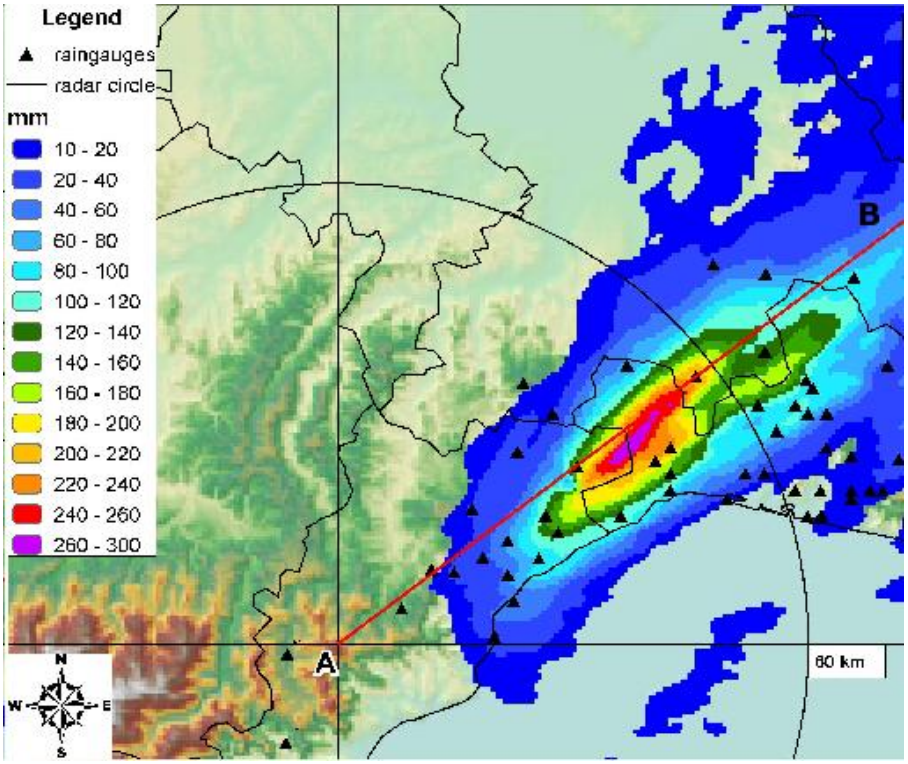



**Figure 3.** Rainfall accumulation since 00:00 UTC to 09:00 UTC on 16 August 2006 by radar and ground station location estimated by $K_{DP}$ algorithm.



The analysis of rain rate along the range for a specific beam (line A–B), shown in Figure 4, put on evidence that all methods are quite close each other up to 50 km from the radar, while the attenuation becomes more important for increasing distances with strong underestimation for methods 1–3.

**Figure 4.** Rainfall accumulation since 00:00 UTC to 09:00 UTC on 16 August 2006 estimated along line A–B with different algorithms.

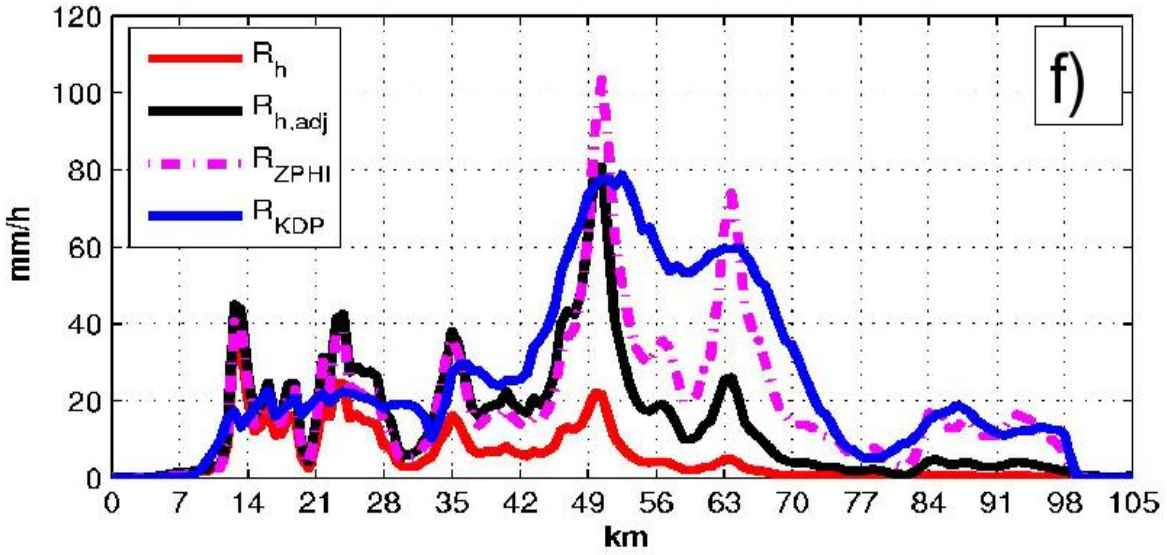



Table 2 shows the results by radar-gauge comparison for $K_{DP}$ algorithm, whose performance is evaluated computing BIAS from:

$$BIAS = (\text{Rain}_{\text{Gauge}} - \text{Rain}_{\text{Radar}})/\text{Rain}_{\text{Gauge}} \quad (2)$$

Table shows that rainfall estimation by $K_{DP}$ algorithm is still underestimated respect to rain-gauge. The most important BIAS is localized at the stations located at a lower altitude and near to the coast, where the radar beam altitude ranges from 400 m to 1,100 m above the ground. This observation suggests that the negative bias may be due to local variation of precipitation with the elevation, likely due to interaction of the orography with the precipitation system.

For this event the attenuation of the radar signal revealed to be locally very high, often exceeding 20 dB. The iterative method for attenuation correction applied here shown a performance comparable with the correction procedure based on $\Phi_{DP}$ (ZPHI), with the notable difference that the former one (algorithm 2) requires rain-gauge measurements to constrain the attenuation. Both adjusted estimates are affected by an important bias, which may be due to both inaccurate radar calibration as well as to vertical profile of precipitation. The specific differential phase $K_{DP}$ allowed to obtain the best agreement with gauges, both in terms of correlation and bias; the resulting 22% normalized bias is also greatly reduced (8%) if the vertical profile of precipitation is taken into account (not shown). It is finally worth noting that the $K_{DP}$ based estimates do not depend on the radar constant or on partial beam blocking [14], which makes this algorithm the most indicated for real time heavy rainfall estimation.

**Table 2**. Comparison between radar derived rain and raingauges measurements.

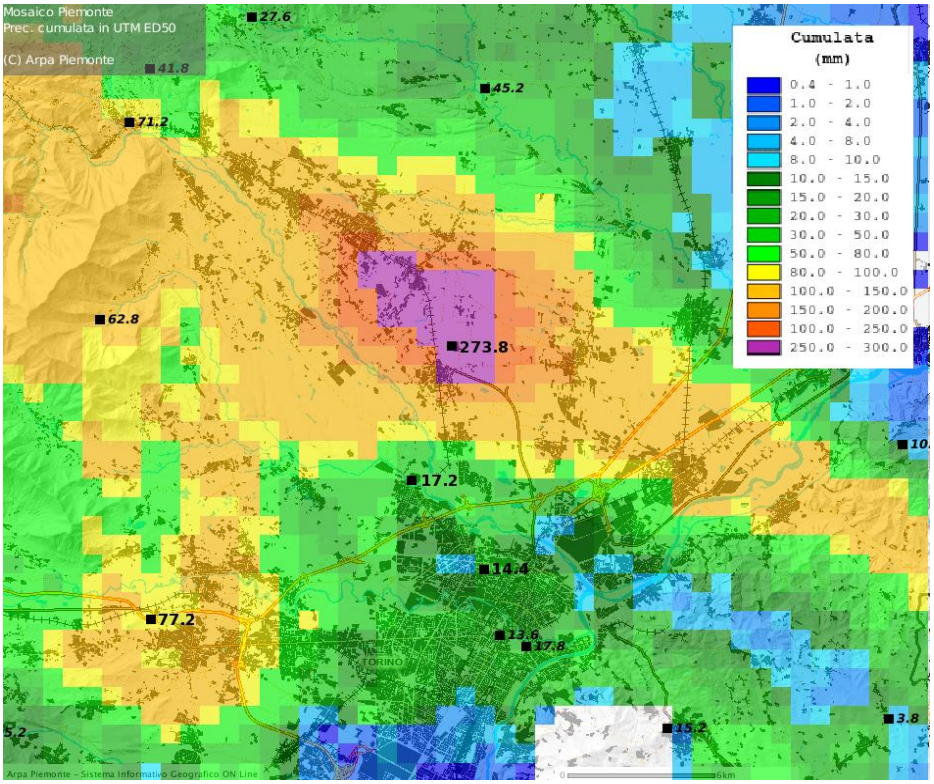
| Site | Altitude (m a.s.l.) | Cumulated rain in raing-auge (mm) | Cumulated rain radar 0.3 ° $K_{DP}$ (mm) | BIAS |
|---|---|---|---|---|
| Fiorino | 290 | 337.0 | 199.8 | –0.41 |
| Passo del Turchino | 598 | 299.0 | 212.0 | –0.29 |
| Mele | 280 | 276.2 | 139.0 | –0.49 |
| Il Pero | 90 | 223.6 | 138.8 | –0.38 |
| Busalla | 358 | 223.0 | 111.6 | –0.50 |
| Sandra | 180 | 194.2 | 85.9 | –0.56 |
| Isoverde | 270 | 193.8 | 118.2 | –0.39 |
| Pianpaludo | 882 | 180.0 | 142.0 | –0.21 |

### *4.2. Flash Flood on 13 September 2008—Turin International Airport*

On the morning of 13 September 2008, a cold front approached the Alps, with a low trough over France, causing severe storms in the western Alps and in the neighboring plains. During the day, the minimum pressure center become deeper and the entire Piemonte experienced strong instability and severe storm activity. The radiosounding performed in Cuneo Levaldigi (WMO station code 16113) at 12:00 UTC showed a cold airmass aloft, with a warm, wet airmass below, with CAPE index of 1,801 J/kg and Lifted Index (LI)-6, confirming strong atmospheric instability. For this event, we only considered the real-time operational rainfall estimation, using the ZPHI algorithm.

Figure 4 shows accumulated rainfall from 06:00 to 18:00 UTC estimated by the Bric della Croce radar and the the precipitation recorded by the regional rain gauges (marked by the labeled squares). The flash flood concerned a relatively small area of 19.30 km$^2$, with maxima values of more the 270 mm in the core, and only 17.2 mm in Venaria Ceronda, about 7 km from the airport. The overall performance of the real-time implementation of the ZPHI is quite good, as testified by the remarkable agreement between the radar estimates and the rain gauge measurements.

**Figure 4.** Accumulated precipitation estimated by radar (colour) and measured by regional raingauges since 06:00 to 18:00 UTC on 13 September 2008.




## 5. Conclusions

Although wide areas are nowadays monitored by dense rain gauge networks, flash flood, sudden severe and localized precipitation, can still be missed. Polarimetric weather radars provide a unique way for monitoring this kind of localized severe weather events, with a high spatial detail and temporal resolution. In particular, the advantage of the polarimetric parameters $\Phi_{DP}$, and its range derivative $K_{dp}$, rely on the fact that phase shift measurements are immune to (1) attenuation, (2) absolute radar calibration and (3) partial beam blocking.

The 16 August 2006 flash flood event on the Ligurian Apennines was considered in this study with the aim to compare the performances of different polarimetric and non polarimetric rainfall estimation algorithms. Both the ZPHI algorithm, in which the differential phase shift $\Phi_{DP}$ is used to account for the signal attenuation, and the $R_{KDP}$ algorithm, where the rainfall rate is linearly related to $K_{DP}$, performed remarkably better than algorithms relying on single polarization. Specifically, the comparison with rain gauges showed an overall large underestimation in case of the $R_h$ algorithm (uniquely based on the horizontal reflectivity), while polarimetric algorithms showed both a reduced bias and better correlation.

Upon operational implementation of the ZPHI algorithm for real time rainfall estimation on the Bric della Croce radar, a second flash flood event has been presented, which affected the area of the Turin international airport (13 September 2008). The operational version of the ZPHI algorithm proved to be robust enough for real-time application, while still providing quite accurate rainfall estimates even in presence of strong attenuation.

**Acknowledgments**

This work have been co-funded by European Union—European funds for regional development—IT-F ALCOTRA Programme—2007–2013 project CRISTAL n° 008. Thanks to anonymous reviewers who helped to improve the manuscript.

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