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J. Van Baelen[1], **Y. Pointin**[1], **W. Wobrock**[1], **A. Flossmann**[1], **G. Peters**[2], **F. Tridon**[1], **and C. Planche**[1]

[1]Laboratoire de Météorologie Physique, UMR6016, CNRS/Université Blaise Pascal Clermont-Ferrand II, 24 avenue des Landais, 63177 Aubière, France
[2]Meteorologisches Institut, Universitaet Hamburg, Bundesstraße 55, 20146 Hamburg, Germany

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Abstract. This paper describes an innovative project which has just been launched at the "Laboratoire de Météorologie Physique" (LaMP) in Clermont-Ferrand in collaboration with the "Meteorologische Institut" in Hamburg, where a low cost X-band high resolution precipitation radar is combined with supporting measurements and a bin microphysical cloud resolving model in order to develop adapted $Z-R$ relationships for accurate rain rate estimates over a local area such as a small catchment basin, an urban complex or even an agriculture domain.

In particular, the use of K-band micro rain radars which can retrieve vertical profiles of drop size distribution and the associated reflectivity will be used to perform direct comparisons with X-band radar volume samples while a network of rain-gauges provides ground truth to which our rain estimates will be compared. Thus, the experimental suite of instrumentation should provide a detailed characterization of the various rain regimes and their associated $Z-R$ relationship. Furthermore, we will make use of the hilly environment of the radar to test the use of novel attenuation methods in order to estimate rainfall rates.

A second important aspect of this work is to use the detailed cloud modeling available at LaMP. Simulations of precipitating clouds in highly resolved 3-D dynamics model allow predicting the spectra of rain drops and precipitating ice particles. Radar reflectivity determined from these model studies will be compared with the observations in order to better understand which raindrop size spectrum shape factor should be applied to the radar algorithms as a function of the type of precipitating cloud. Likewise, these comparisons between the modeled and the observed reflectivity will also give us the opportunity to further improve our model microphysics and the parameterizations for meso-scale models.

Correspondence to: J. Van Baelen
(j.vanbaelen@opgc.univ-bpclermont.fr)

1 Introduction: project objectives

The primary goal of this project is to develop a robust, mobile, low cost X-band radar in order to localize and quantify precipitation with high spatial and temporal resolution over areas equivalent to urban areas, small catchments basins or even extended agriculture domains. Such a tool is not yet readily available in the meteorological community as only a few commercial or one-of-a-kind research dedicated systems exist. Although limited in its range of capabilities, such a radar system can adequately support a wide range of scientific studies on convective and precipitating system processes due to its high spatial resolution and its high mobility. Additionally, it offers various civil applications involved with rain estimation such as water runoff and retention basin management, flood risk warning, as well as precipitation monitoring for agriculture, while its low cost would make it easily accessible to the user community.

As it is the aim of the project to provide reliable estimates of rainfall rate with a very high spatial and temporal resolution, comparative studies with precipitation estimates determined with other remote sensing or in-situ instruments will also be carried out. Furthermore, radar reflectivity is a volume integrated measure of the number/size distribution of liquid and solid hydrometeors. Thus, in order to better understand the relationship between radar reflectivity and the size distribution of the hydrometeors, this radar work will be accompanied by cloud model studies within a 3-D, highly

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resolved dynamical frame. Likewise, the use of a detailed bin resolved mixed-phase microphysics model developed at LaMP for cloud and precipitation spectra will make it possible to determine the dependence of the raindrop size spectrum shape parameter on location, time, and type of the measured clouds such that advanced restitution algorithms can be developed. In addition, the comparison of the simulated precipitation with the observed reflectivities will allow us to improve our understanding of the microphysical processes responsible for the rain formation and thus will result in the improvement of the precipitation parameterizations used for synoptic and meso-scale models. Hence, in this work, iterations between the radar measurements and the modeling efforts will advance the development of both areas of the project.

2 General scientific background

2.1 Cloud drops life cycle

Lifting of moist air parcels, be it due to convection, orographic forcing, or any other mechanism, will cause their temperatures to fall and approach dew point temperatures. Then, cloud droplets nucleate when water vapor condensate on aerosol particles which act as condensation nuclei. Such condensation nuclei, e.g. aerosols, can be solid particles or hygroscopic liquids, both of natural or man-made origin, and present variable nucleation efficiency. To condensate around the nuclei a super-saturation is required. Once the droplets form, condensation is too slow a process to generate precipitating drops within the usual lifetime of a cloud. Thus, coalescence of colliding drops is needed to produce sizable drops. The smallest drops are essentially spherical and tend to become more oblate as they grow (Pruppacher and Pitter, 1971). Larger drops deform to get a flattened then concave base. That structure becomes unstable and tends to breakup into smaller drops. Thus, the spectrum of drops size distribution tends towards equilibrium between coalescence and breaking-up of drops (Srivastava, 1974). Most mid-latitude clouds, however, pass via the ice phase for precipitation formation. Here, in an initial state, certain aerosol particles called IN (Ice forming nuclei) form small ice crystals or small droplets freeze. The small initial crystals grow rapidly by vapor deposition and then collide with other crystals or liquid drops to reach the size of graupel particles or snow flakes. Depending on the zero degree altitude in the atmosphere, these graupel particles can melt before reaching the ground. Here, equally in the final stage an equilibrium distribution can be reached allowing the representation of the size distribution by a constant raindrop size spectrum shape factor. For a thorough review of cloud physics, the reader is referred to Rogers and Yau (1989) or Houze (1993).

2.2 Radar measurement of precipitation

Since the advent of radar meteorology after the Second World War, it has been a continuous quest in the meteorological community to design ways to retrieve precise localization of precipitation and quantification of rain rates with radars. This endeavor has proven difficult and nowadays much research work is still being carried out on that topic.

Given that the weather radar returns are caused by backscattering of the electromagnetic waves upon the hydrometeors present in the illuminated radar beam, an accurate estimate of rainfall rates requires a detailed knowledge of the drop size distribution of rain (DSD: the number density of water droplets in a unitary volume as a function of their diameter).

Although it is not a unique representation, it is customary to use the Marshall-Palmer relationship to describe the DSD. This is an exponential formula with two parameters which have been shown to be dependant on the rain fall rate (R). Other distributions, such as truncated exponential function, Gamma functions, are sometimes used in the literature. In fact, the actual drop size spectra can differ quite significantly from a unique representation according to the type of rain encountered which can be not only geographically and seasonally dependant but can also vary within a complex precipitating system (Battan, 1973; Joss and Gori, 1978). For radars with a single parameter measurement capability (i.e., single frequency, no dual polarization), it is possible, under some assumptions and with careful selection of operational coefficients, to estimate the rain fall rate from the measured reflectivity factor (Z). For further readings and references, one would suggest Wilson and Brandes (1979) and the books by Doviak and Zrnic (1984), and Rinehart (2004).

Currently, there are two main kinds of radar systems in use in the meteorological community. The first ones are the operational weather radars from the national weather services. These radars are most often S- or C-band systems with an extended range (a couple hundred of kilometers) in order to survey as wide an area as possible. Many of them have volume scan and/or Doppler capabilities while they are usually operated under fixed pre-set observation schemes. They all have in common to be very expensive. The second category of radars is the research radars. They are most often one of kind type of radars designed to explore new technologies and offer new insights into meteorological research. They can be operated in S (rarely), C (sometimes), or X (most often for more portability) band. Most of them are Doppler and have dual polarization and/or dual frequency with volume scan capabilities. These are priceless research tools but are also very expensive. Looking into existing radar systems in the research community which could prefigure our project, one could mention the "Doppler on Wheels" radars in the US for mobility (Wurman et al., 1997), or the French X-port radar for precipitation studies (Gosset et al., 2004), although these are much more expensive when compared to our goals.

Also there exists a few commercial “mini” weather radars, but they are still an order of magnitude more costly than what we target in this project. Finally, the closest development to date which resembles our project is a radar built by the Danish Hydrological Institute (Rollenbeck and Bendix, 2005). It also uses a modified navigation radar, but has kept the original wave-guide antenna such that the beam characteristics limit the application of such a system to stratiform rain over fairly flat terrain.

2.3 Clouds micro-physical processes modeling

Concerning actual models to represent clouds, the literature displays a large variety of choices. The models have a different complexity concerning the dynamics, going from a simple parcel model approach, passing by 1-D and 2-D representations, until the full 3-D representation of the model domain, with large scale forcing and interactive grid nesting. Equally, concerning the microphysics different schemes of increasing complexity exist. Most global models only treat a single variable for condensed water, while synoptic and meso-scale models consider up to five reservoirs for small and large drops, small and large ice particles and snow. Only a few models exist that follow explicitly the drop and ice particle spectra at every grid point of the model. And still less of these models are coupled to a full 3-D framework. Some examples of such models were developed in Israel (Lynn et al, 2005), and the US (Ovtchinnikov and Kogan, 2000), and recently at LaMP (Leporini, 2005). Equally at LaMP activities exist to simplify the spectral microphysics models to bulk mode parameterizations (Caro et al, 2004). These parameterizations need an assumption on the shape of the hydrometeor spectra which often lack justification.

3 The observational strategy

The rationale behind the current project is to develop the necessary know-how to retrieve good quality estimates of precipitation with the newly developed X-band radar (Fig. 1) by comparing the retrieved parameters with other available remote sensing and in-situ measurements, as well as cloud microphysical processes modeling results.

3.1 The X-band precipitation radar

The base of the radar consists of a modified version of commercially available navigation radar in order to provide 2-D maps of reflectivity. However, in order to improve the return signal characteristics, and thus the rain estimation capabilities, the antenna has been changed to an off-set parabola in order to obtain a pencil beam, while the signals are accumulated over successive rotations of the antenna. The radar characteristics are summarized in Table 1. The typical operation mode of the radar corresponds to 30 s time integration, 60 m range integration, 2° azimuth integration.

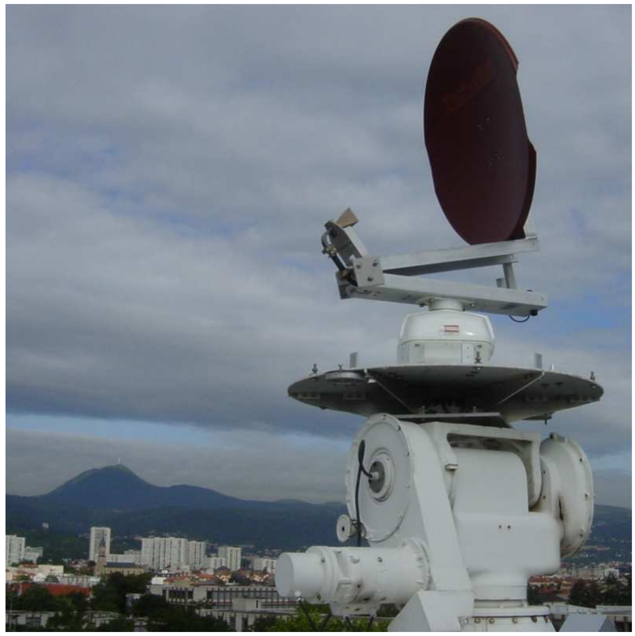

Fig. 1. View of the Clermont-Ferrand X-band precipitation radar without its protective radome. Parts of the city of Clermont-Ferrand and the Puy de Dôme are visible in the background.

3.2 Development strategy and supporting measurements

Given that the radar considered is a single parameter system in order to keep its cost low; there is neither dual frequency nor polarization diversity implemented. Thus, there are a few limiting factors that must be considered in our project in order to obtain reasonable rainfall estimates.

First of all, the $Z-R$ relationship is not unique and is highly dependent upon the type of precipitation encountered and its associated drop size distribution (DSD) (Battan, 1973; Doviak and Zrnic, 1993). However, our radar exhibits a very high spatial resolution which works in our favor by reducing the heterogeneity of the atmospheric environment within the sampled volume.

To help us in defining the most appropriate reflectivity/rain rate (or $Z-R$) relationships for our radar but also to calibrate our X-band radar, we compare the X-band radar reflectivity with direct measurement of the reflectivity and drop size distribution evaluated by a vertically looking K-band micro-rain radar (Peters et al., 2002; Peters et al., 2005) which has been calibrated in laboratory using the procedures described in Peters et al. (2005). Then the X-band radar calibration is performed by statistical comparison with micro rain radar measurements observed during selected rain event.

As the X-band radar beam intersects with the micro rain radar beam, this gives us insights into the different rain intensities and rain regimes and their associated X-band radar signal reflectivity. An example of direct comparison of the X-band radar and MRR reflectivity in their common volume

Table 1. X-band radar operational characteristics.

Frequency	9410±30 MHz
Peak power	12 kW
Pulse width/Pulse repetition frequency	0.8 μs/600 Hz or 0.3 μs/1200 Hz or 0.08 μs/2100 Hz
Sampling rate	10 MHz
Scan rate	24 revolutions per minute
Antenna gain	30 dB
Half power beam width	2.4°
Beam elevation	Fixed elevation during operation but mechanically adjustable from 2 to 20°
Range (expected maximum useful)	20 km

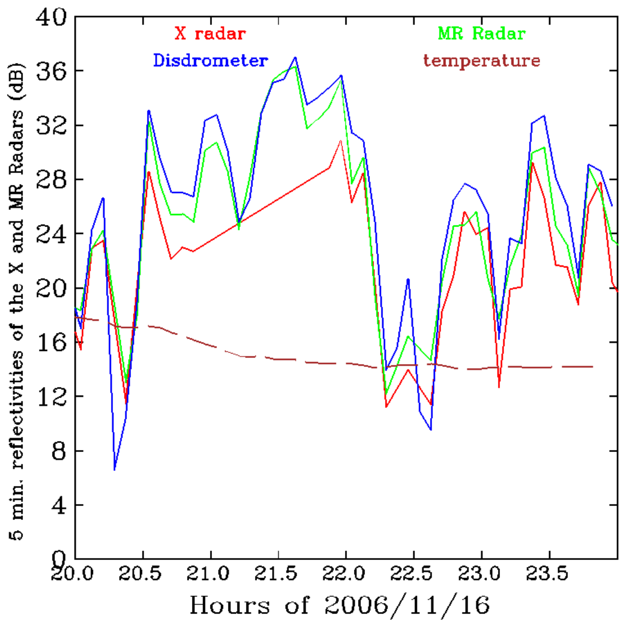

Fig. 2. Reflectivity from the X-band radar (red curve), the MRR (green curve) and estimated from the disdrometer measurements (red curve) while the surface temperature is provided by a dash line.

is provided in Fig. 2 along with a ground estimate of such reflectivity derived from the available disdrometer measurements. While the agreement is very good between these various curves, long term measurements in common atmospheric cell volumes with these two instruments under various precipitation conditions will provide us with a valuable database from which to assess different $Z-R$ relationships and their domain of validity. Indeed, it is well known that precipitation characteristics can be sensibly different according to various rain regimes (for example stratiform, convective, etc.) but can also vary significantly within a single precipitation event (i.e., differences between the onset and the trailing end of the rain system, internal sub-structures and enhancements). Therefore, the keystone of our approach is to be able to identify rain regime classes based on subjective criteria such as intensifying or decaying rain intensity (Van Baelen et al., 2006, 2009), or statistical temporal stability (Clemens et al., 2008)

Likewise, a network of rain-gages and disdrometers provides “ground truth” for the validation of rainfall rate estimates which will be derived from the radar measurements. Although, some caution must be used in such comparisons (Wilson, 1979), they are the back-bone of validation of rainfall estimates by radars. However, it is important to have at disposal a large enough set of ground measurements in order to be able to picture accurately the rain rate distribution and its variability on the ground as it has been demonstrated that the denser the network the more accurate the rainfall field retrieval can be (Hildebrand et al., 1979). Thus, we need to be able to capture the rainfall at the various locations of the precipitation system, while accounting for the radar spatial resolution. Currently we rely on a network of 18 rain gages all within 10 km of the radar site.

Another limitation with our radar will arise from the X-band signal attenuation associated with the propagation of the electromagnetic wave through rain. To circumvent this effect, we apply the well known Hitschfeld and Bordan (1954) algorithm with statistically determined parameters based on the study of multiple rain events. However, this method has some limitations because it relies on a-priori drop size distribution factors but also in case of strong precipitation and precipitation gradients. Therefore, we limit attenuation correction to 10 dBz beyond which value we consider that it is no longer possible to determine a realistic attenuation correction. Hence, we are currently considering alternative calibration methods based on differential ground target reflection between rain ad no-rain events. These recently developed methods should allow for retrieval of the path-integrated attenuation following the work of Fabry, 2004; Delrieu et al., 1999a, b. Under some assumptions, the attenuation measured is representative of the scan region affected by rain. This method could also be applicable in the context of partially filled beams (Gosset and Zawadzki, 2001). Although this area of work and development is still uncertain, we think that the use of multiple micro-rain radars positioned along a single X-band radar beam in the direction

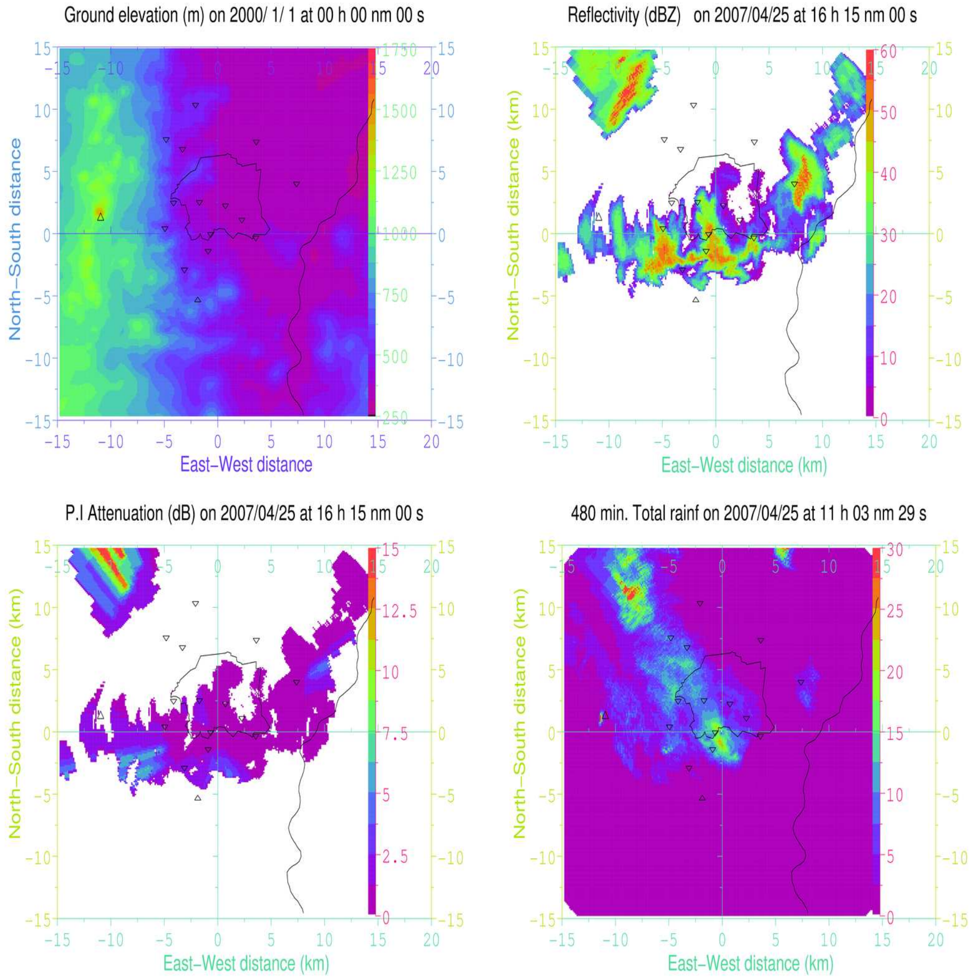

Fig. 3. (a) Radar environment orography with the Puy de Dôme to the West and the markers to identify the rain-gages location while the solid lines indicate the contour of Clermont-Ferrand and the Allier river; **(b)** Reflectivity display of the X-band scanning radar; **(c)** Estimated Path Integrated Attenuation display for the X-band scanning radar; **(d)** Derived 8 h accumulated precipitation display with the X-band scanning radar.

of an identified mountain echo such as the nearby Puy de Dôme (∼11 km from the radar) will be very beneficial. Such measurements will enable the estimation of partial attenuation along the X-band radar beam according to the rain field experienced and provide useful information on the attenuation along the path. Hence, we expect to complement our experimental set-up with additional micro rain radars soon.

4 The cloud micro-physical model

The dynamic framework employed in the present study is the three-dimensional model developed by Clark and co-workers (e.g. Clark, 1977, 1979; Clark and Farley, 1984; Clark and Hall, 1991). This model is an established tool for the simulation of the airflow and the formation of clouds over complex terrain on small meteorological scales (see, e.g., Clark and Gall, 1982; Clark et al., 1994; Bruintjes et al, 1994, 1995; and Wobrock et al, 1997, 2003). The present non-hydrostatic version of the code uses a terrain following vertical co-ordinate with a user-defined spacing.

Furthermore, to describe the system microphysical characteristics within this work, we use the model DESCAM, i.e., the Detailed **SCA**venging and **M**icrophysical model, as discussed in Flossmann et al. (1985, 1988). It has recently been extended to a bin resolved treatment of the ice phase (Leporini, 2005). This microphysical model is linked to the dynamics in a fully interactive 3-D manner and allows the representation of the cloud that is observed by the radar in a highly resolved manner, concerning both the spatial and the microphysics resolution. This model is used to identify in cloud life periods where a constant hydrometeor size distribution spectrum shape parameter can be found. For this, the model will be extended to calculate radar reflectivity from

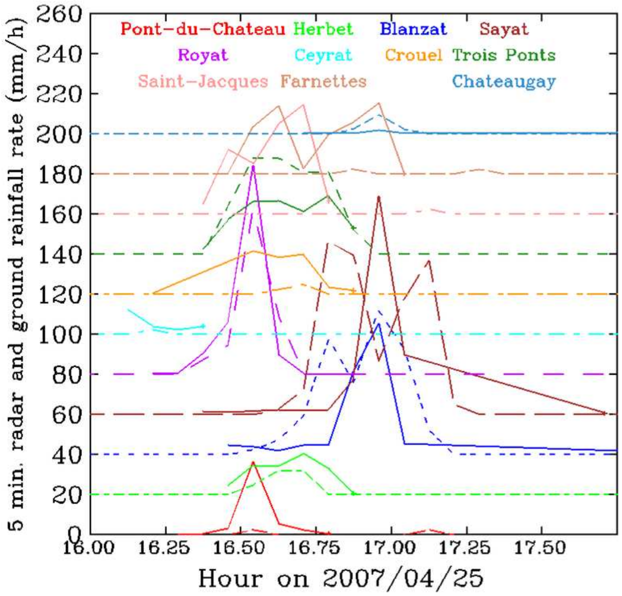

Fig. 4. Time series of 5 min radar and ground rainfall rates for the different rain-gauge sites. Each successive site is augmented by 20 mm/h for visibility. Dash lines for rain gages observations, solid lines for X-band radar estimations.

the droplet, ice and mixed phase particle spectra. They will be compared to the radar observations.

In a second step, we will adapt the microphysical code such that the drop and ice particle size distributions are parameterized by generalized gamma distributions (Caro et al., 2004). To do so, the parameters obtained by the detailed calculations and in agreement with the radar observations will be used to improve the parameterization of the spectra. This parameterized code can then be more easily applied to simulations of clouds on the synoptic-scale covering several 1000 km.

5 Examples of ongoing investigations

Figure 3 illustrates some of the preliminary work we have carried out with the set of instruments currently deployed. The example shown corresponds to the 25th of April 2007 event with was characterized with some intense localized precipitations over the area of Clermont-Ferrand.

Panel (a) shows the local orography surrounding the radar. It appears clearly that the city of Clermont-Ferrand, marked by a solid line, is bordered to the west by mountainous terrain, with a high point being the Puy de Dôme (indicated by a cross) about 1000 m above the city floor. Likewise, the east side of the city opens to flat agricultural lands.

In panel (b), the 30 s, 60 m resolution radar reflectivity, expressed as $Z{=}C\,P\,r^2$, where P is the received power, r the range and C a calibration constant, is shown after ground clutter has been removed. Individual precipitation cells of only a few hundred meters are clearly visible.

In the current application, the ground clutter is determined as a 5 min average of received power over the entire area visible to the radar under clear sky conditions, assuming that when no hydrometeor is present only clutter will produce significant echo power, while time averaging will limit fluctuating noise effects. The corresponding mask is then subtracted from any subsequently measured scene. That approximation is mostly correct due to the short range of the radar observations. However, in case of light rain event, wet structures such as rooftops, antennas, etc. can provided slightly increased clutter returns which will induce possible errors in the measured reflectivity and, hence, rain rate estimates. We are aware of this limitation but we don't have yet defined or implemented a method to deal with this limitation.

The Path Integrated Attenuation derived using the algorithm of Hitschfeld and Bordan (1954) which is sensible as long as the attenuation is less than about 10 dBZ is shown in panel (c). Once data have been corrected for attenuation, rain rate is calculated using, in this case, a standard Marshall and Palmer (1948) $Z-R$ relationship panel. That is what is presented in panel (d): the resulting 8 h accumulated rain field associated with this event.

In the future, the study of the common volume between the X-band radar and the vertically pointing MRR will allow us to define $Z-R$ relationships specific to the rain regime which characterizes the event (or parts of the event) considered. Likewise, more evolved attenuation correction schemes will be implemented and tested.

In order to asses our results (i.e., rainfall rate estimates with the X-band radar), we performed comparisons with the various rain gauges available through out the area. Figure 4 shows the time series of 5 min averaged rainfall rates (in mm/h) for the reporting rain gages at that time, each in a different colour, while the dash lines correspond to the rain gage data and the solid lines to the radar estimated results. Overall the agreement is satisfactory although discrepancies can be noted while the radar seems to produce overestimates at times. Of course we need to verify such trend on many more cases and also adopt adapted $Z-R$ relationships rather than a standard distribution.

6 Conclusion and prospective

The instrument ensemble that has been put together to monitor the Clermont-Ferrand basin should provide a very interesting data base over time in order to study precipitation heterogeneity, propose rain regime classification at scales equivalent to or even smaller than the event size itself, and develop adapted $Z-R$ relationships for improved rain rate estimation. Furthermore, the high spatial and temporal resolution should provide new insights into the internal dynamics of convective and precipitating events.

Early results are encouraging and indicate that the high resolution of the radar coupled with the rain spectra measurement of the MRR will provide very useful and accurate products within its scope of applications.

Beyond its scientific involvement in microphysical studies of cloud and precipitation system with its high space and time resolution, the proposed radar suite appears also well suited for a wide range of surveillance and risk management operations (such as flash flood warning for civil security, urban communities storm basin management, agricultural surveillance and monitoring) while its cost will make it affordable to such civilian and private entities. Therefore, we plan to demonstrate the radar and system capabilities and develop the necessary environment for a highly mobile system within a real time display environment of the various radar measurements and products as well as model simulations.

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