APPLICATION OF THE HYDROLOGIC VISIBILITY CONCEPT TO ESTIMATE RAINFALL MEASUREMENT QUALITY OF TWO PLANNED WEATHER RADARS

by

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ABSTRACT

This paper presents a practical application of the "hydrologic visibility" concept to select the future site of two planned weather radars of the French national network ARAMIS. This selection was realised by simulating the errors in radar rainfall measurement due to interactions of the radar beam with relief, and to the vertical variation of the radar reflectivity with altitude. Results show the interest of these simulations to optimise the radar location according to the objectives of radar coverage. Beyond these results, this paper highlights aspects interesting for hydrology: this type of simulation can be used to assess the radar measurement quality before initiating a quantitative exploitation of radar data, and before making a comparison or a combination with rain gauge data.

KEYWORDS:

weather radar, hydrologic visibility, rainfall, measurement, quality, simulation

1. INTRODUCTION

Weather radar measurement of rainfall is subject to a range of phenomena which affect the accuracy of the surface precipitation estimates, these difficulties increasing with relief and with the altitude of the radar site (Joss et Waldvogel, 1990). Since a few years, hydrologists have developed the concept of "hydrologic visibility" of a weather radar to describe the quality of the radar rainfall measurement over a region, a catchment area, or an agglomeration (Pellarin et al., 2002). From this concept, the LTHE (Laboratoire d'étude des Transferts en Hydrologie et Environnement, Grenoble, France) has developed a software called VISHYDRO to estimate this quality. This software, perfected in the framework of research actions, integrates in a very detailed way the effects of ground clutter and masks due to the interactions of the radar beam with relief, and the effects of vertical variations of radar reflectivity with altitude. Data required for these estimations are physical characteristics of the radar, a digitalised terrain model (DTM), and one (or a set of) vertical profile(s) of reflectivity (VPR) representative for the region.

In 2002, VISHYDRO was used in two studies with operational interest for the French Meteorological Office (Météo-France). The goal was to simulate the hydrologic visibility of two planned radars of the French national ARAMIS network: the future radar of the Tarn-Aveyron region (southern France) and the future radar of the Franche-Comté region (northeast France). The objective was to compare *a priori* the advantages and disadvantages of several sites pre-selected by Météo-France for establishing these new radars in order to extend and upgrade the ARAMIS network. The determining criterion was the quality of the rainfall measurement over the region and particularly over several basins of priority interest for end users.

This paper synthesises the results obtained and highlights the aspects interesting for operational hydrology: the important and fast spatial variations of the radar rainfall measurement quality, and the interest to precisely estimate the effects of each source of error before a quantitative use of radar data.

2. PRINCIPLE OF THE SIMULATIONS

The VISHYDRO software uses algorithms described in detail in Delrieu et al. (1995) and Pellarin et al. (2002). The simulations are realised in two steps in order to estimate the errors on radar rainfall estimations induced by ground clutter, masks and non constant VPRs, for a given elevation angle of the radar beam.

2.1. Simulation of the "radar beam - relief" interactions

The first step is a numerical simulation of the interactions between radar beam and relief (figure 1). This simulation uses:

- a detailed description of the resolution volume of the radar measurement, taking into account the entire main lobe of the radar beam, an angular weighting function describing the antenna power diagram, and a range weighting function accounting for the pulse length and the characteristics of the radar receiver ;
- a DTM allowing to estimate the ground area illuminated by each resolution volume for the given elevation angle, and the incidence angle of the radar waves on each element of this surface ;
- an electro-magnetic model adapted for the mean nature of the ground surface in order to characterise the backscattering coefficient of ground as function of the radar parameters (wavelength, angle of incidence, polarisation of the waves, etc.).

For the given elevation angle, the results are: (i) a precise estimation of the area of the illuminated ground surface ; (ii) the apparent reflectivity (Z_g) of the ground echoes ; (iii) the part of the beam and the percentage of the beam power masked beyond each ground echo.

2.2. Simulation of the hydrological quality of the radar measurement

The second step is a simulation procedure estimating for each resolution volume, the value of the error affecting rainfall estimations at ground level, by integrating results of the first step and one or various models of VPR chosen relevant for the region (climatological approach) and supposed invariable in the radar coverage. The projection of the resolutions volumes on the ground surface allows to estimate the map of error affecting rainfall estimations for each point (x,y) of the radar coverage. This estimation is based on four hypothesis:

- H1: the total backscattered power measured by the radar is the sum of the backscattered power induced by rain and ground echoes. Consequently, the total measured reflectivity Z_m (in mm^6/m^3) over a point (x,y) is the sum of the rain reflectivity (Zr) in the radar resolution volume and of a possible ground clutter contribution Z_g:

$$Z_m(x,y) = Z_r(x,y) + Z_g(x,y) \quad (1)$$

- H2: The rain reflectivity Z_r is assumed to be a combination of two orthogonal functions describing the horizontal rainfall variability at ground level Z_{ro}, and the vertical variability of the reflectivity Z(h). Z(h) is assumed constant for the entire radar coverage in the simulation, and defined by the VPR model. Thus, for a given elevation angle θ of the radar beam, it is possible to define a spatial $Z_{a\theta}$ function representing for each point (x,y) the measurement error of Z_{ro} due to the VPR and masks effects:

$$Z_{r\theta}(x,y) = Z_{a\theta}(x,y)\, Z_{ro}(x,y) \quad (2)$$

  $Z_{a\theta}(x,y)$ is estimated by a numerical integration over each resolution volume, and depends on the VPR pattern, the beam part masked before this volume, and the radar beam characteristics (elevation angle, beamwidth, antenna power diagram):

- H3: the Z-R relationship used to transform reflectivity in rainfall intensity is of the $Z = a\,R^b$ type, with parameter b supposed known and invariable in the radar coverage.
- H4: the attenuation of the radar beam power by rainfall is not taken into account.

From these assumptions, it is possible to express Z_m at the elevation angle θ over each point (x,y) as:

$$Z_{m\theta}(x,y) = Z_{a\theta}(x,y)\, Z_{ro}(x,y) + Z_{g\theta}(x,y) \quad (3)$$

The error on reflectivity measurement can be expressed in dBZ:

$$\Delta z_\theta(x,y) = 10 \log_{10}[Z_{a\theta}(x,y) + Z_{g\theta}(x,y)/ Z_{ro}(x,y)] \quad (4)$$

and the error value affecting the rain rate estimation R_θ* (in mm/h) for the given elevation angle θ, is the QR_θ ratio:

$$QR_\theta(x,y) = R_\theta(x,y)^*/R(x,y) = [\ Z_{a\theta}(x,y) + Z_{g\theta}(x,y) / Z_{ro}(x,y)\ ]^{1/b} \quad (5)$$

QR_θ represents the hydrological quality of the radar measurement for the θ elevation angle, and for area not concerned by ground echoes this ratio is independent of rainfall (excepted the b parameter of the Z-R relation-ship), but dependent on the VPR model chosen and of the radar beam characteristics. $1/QR_\theta$ represents the theoretical value of the correcting factor of the VPR and masks effects for the elevation angle of measurement θ.

For area affected by ground echoes, $Z_{g\theta}$ value is not null and the QR_{θ} value depends on the Z_{ro} reflectivity induced by rainfall: the more significant the rain is, the less the ground echo has an effect. In the simulation procedure, Z_{ro} is assumed constant in space and its value is a parameter. Although the simulation of ground clutter is subject to significant uncertainty, the result indicate the pixels for which the ground clutter effect can be regarded as significant in the radar rainfall measurement for the Z_{ro} value selected.

2.3. Limits of the simulations

These simulations only consider interactions between the main lobe of the radar beam and relief (described by the DTM). The simulation procedure do not take into account clutter an mask effects due to anthropogenic sources, and the side lobes of the radar beam were not considered (these lobes can induce ground echoes close to the radar site). Equally, in this software version the assumed radar waves propagation model corresponds to standard conditions, and the anomalous propagation phenomenon (anaprop) is not considered (this phenomenon can induce variable ground clutter). Another limit concerning simulation of ground echoes, is the utilisation of a single model to characterise the mean backscattering coefficient of ground for the region: an improvement would be to take into account spatial variation of this coefficient. (Observe that in real situation ground echoes also vary depending on variations in the vertical positioning of the radar antenna, and vary in time according to modifications of the ground surface).

Concerning the precision required for the DTM, Pellarin et al. (2002) showed that the results integrated over square grids of 1 km resolution are not very different for various DTM if the spatial resolution of the DTM is lower than 200 m. In the two studies related, the DTM resolution was 250 m and it was confirmed that the results were similar with a 75 m resolution DTM.

Finally, it is important to insist on the fact that the estimated QR_{θ} values must be interpreted according to the VPR model chosen. The VISHYDRO software allows to quickly carry out simulations for a great number of VPR, offering the opportunity to study the climatological variability of the simulated errors. However, the required VPR climatologies were not available when this work was realised, and only few types of VPR were selected and used. Note that the identification of regional VPR climatologies is an important task, and Météo-France is presently establishing such climatologies for several regions of France.

2.4. Application in the two studies

In the two studies, the simulations were used to compare advantages and disadvantages of different pre-selected radar sites. Météo-France pre-selected these sites by a first analysis, tacking into account for a great number of radar locations, masks and ground echoes, accessibility of the site, possibility and cost of building the radar, but not the effects of vertical variation of reflectivity which increase with range and with the elevation angle of measurement. The main challenge of the studies was to integrate these effects into the radar sites evaluation.

Some VPR models were selected to be relevant for the two case study regions. The value of the Z_{ro} reflectivity induced by rain at ground level was set as 1000 mm^6/m^3, corresponding to the climatological mean rainfall of about 3 mm/h. The b parameter value was set equal to 1.6. The values of the QR ratio were calculated for ranges varying from 0 to 256 km, in accordance with the characteristics of the operational radar images provided by the ARAMIS network.

These simulations produced maps of QR ratio representing the “hydrologic visibility" from each radar site in function of the VPR and of the beam elevation angle. For areas without strong ground echoes (i.e. $Z_g(x,y) / Z_{ro}(x,y) < 0.25$ corresponding to ground echoes below 24 dBZ for $Z_{ro}(x,y) = 1000\ mm^6/m^3$), these results were also used to estimate mean $\overline{QR}$ values of the QR ratio over drainage basins of priority interest:

$$\overline{QR} = 1/S \int_x\int_y QR(x,y) \qquad \text{if } Z_g(x,y) / Z_{ro}(x,y) < 0.25 \qquad (6)$$

with S the surface of the basin. The total surface S_g of ground echoes above the threshold 0.25 $Z_{ro}(x,y)$ has also been estimated for each basin and each elevation angle. We can note that the mean $\overline{QR}$ values could combine over- and under-estimations of the radar measurement. In the presented studies, this effect was not a problem and this simple criterion was preferred to others. Maps of QR ratio and estimated $\overline{QR}$ and S_g values have been used together to compare the radar sites possibilities to achieve the best hydrologic visibility both for all the region and the selected basins.

This comparison was realised by tacking into account the possibility of estimating rainfall at ground level by combination of measurements realised at different beam elevation angles: this combination allows to select the best quality data, particularly in cluttered or masked areas, and the operational measurement procedure of the ARAMIS radars permit this treatment. Nevertheless, QR maps resulting from such combination was not produced in this work.

In this paper, we don’t present details of the numerical results (depending on the VPR used), but only the general results of the analysis for both case studies.

3. CASE STUDIES

In both studies, the radar was of the C-band type (5.3 cm wavelength) with a 1.1° beamwidth at half power. The two considered regions include large mountainous areas, and QR ratio was simulated for two elevation angles of measurement (0.4° and 1.4°) in accordance with the operational procedure of measurement envisaged for these radars. However, in the second study additional angles were also used for some simulations.

3.1. The Tarn-Aveyron radar case:

The first study aimed to simulate the hydrologic visibility for two pre-selected sites of the future Tarn-Aveyron radar. The region includes the south of the Massif Central mountain in the north, the Pyrenean mountain in the south, and the Mediterranean coast in the south-east. The relief of the interest area varies from 0 to 1700 metres. Eight drainage basins have been classified in five decreasing levels of priority in accordance with the interest of the radar measurement for local authorities (the surfaces of these basins vary from 300 to 12 000 km²). The two pre-selected radar sites were situated at the northern limit of the first priority basin, and the surface of the eight basins was mainly included in a circle of 50 km around each radar site, and almost completely inside a circle of 80 km. The altitudes of the two pre-selected sites were almost the same (669 m and 671 m), and the distance between the two locations was 22 km.

Two models of mean VPRs were selected from series of hourly VPR identified in the Cevennes region, in the south-east of the Massif Central (Andrieu et al., 1997):

- a mean VPR corresponding to a profile without bright band and with a moderate vertical development: this profile was assumed to be constant below 1200 m of altitude, and presented a progressive decrease more dramatic with altitude from 1200 m to 2800 m.
- a mean VPR characterised by a significant bright band situated at 2800 m of altitude, and by a vertical development of precipitation reaching 3600 metres. This profile was similar to the previous VPR below 2000 m of altitude, and the peak of reflectivity reached +12 dBZ at 2800 m of altitude, but only +3 dBZ compared to the reflectivity at ground level.

The simulations results were unambiguous: by combination of the measurements realised with the two elevation angles, the radar coverage quality would be better from the first site, both for all the region and most of the basins of interest. This result was due to masks much more significant for the second site than for the first one, and to a distance from the radar to the basins more limited for the first site. The study confirmed the first analysis of Météo-France, and the choice between the two locations was thus clear.

3.2. The Franche-Comté radar case:

The second study aimed the simulation of hydrologic visibility for three pre-selected sites of the future radar of the Franche-Comté region. The area of interest comprised the Vosges mountains and the Alsace plain in the north, the Saône basin in the west, and the first foothills of the Jura mountains in the south (figure 2). Relief inside this area varies from 120 to 1300 metres. Six basins of interest have been classified in four levels of priority. Nevertheless, three of these basins could be correctly covered by other operational or planned radars. Thus, the determining criterion to select the optimal location of the radar was essentially the hydrologic visibility over the region and for three basins (two of first priority level, one of priority level 2).

The important variability of the relief and the distance between the basins made difficult the selection of this optimal location. The maximal distance between the three radar sites were significant (up to 45 km). The surfaces of the three determinant basins varied from 275 to 4 050 km², and were largely situated outside a circle of 50 km around each radar.

Information on the vertical structure of reflectivity not being available in the region, three models of mean VPRs were assumed in accordance with profile patterns observed in other region and adapted according to the variations of the normal monthly temperatures for the Franche-Comté region (figure 3):

- a mean VPR (VPR1) corresponding to a profile without bright band and with a vertical development of precipitation reaching 3800 metres.
- a mean VPR (VPR2) corresponding to a profile with a moderate bright band situated at low altitude (1600 m), and with a moderate vertical development of precipitation (2800 metres). This profile was similar to VPR1 below 1000 m of altitude.
- a mean VPR (VPR3) characterised by a more important bright band situated at 3000 m of altitude, and with a vertical development of precipitation exceeding 4000 metres. This profile was similar to VPR1 below 2000 m of altitude.

It is important to note that in this case study, the altitudes of the three pre-selected sites were very different, respectively 1050 m, 520 m, 770 m. Accordingly, the results indicated that the three pre-selected sites represented particularly distinct measurement conditions in this difficult area:

- Site 1 had the advantages and the disadvantages due to its high altitude (1050 m). Simulations showed that masks should be not very significant, but that radar measurement would be realised at high altitude from this site, on account of the radar altitude and of the fact that this site was at the greatest distance from the three determinant basins. This would favour significant underestimations even with low measurement elevation angles in case of strong vertical decrease of reflectivity over the basins of interest. Measurements with higher angles (as 1.4° and more) could be much more often not exploitable from this site than from the others, which could strongly limit the interest of a volumetric exploration of the atmosphere. Figure 4 shows the maps of the QR ratio obtained with VPR1 for this pre-selected radar site, and for the two elevation angle 0.4° and 1.4°.
- Site 2 was both the nearest to the three determinant basins and located at the lowest altitude (520 m). Situated in proximity to significant Vosges relief, simulations showed that the radar could be operated only with high elevation angles to cover the two determinant basins located in the northeast area. This constraint would be a problem for measurement of precipitation not very developed in altitude. Equally, radar measurements for low elevation angles over the entire Franche-Comté region would be very degraded by many significant masks, the mean hydrological visibility for the region being lowest from this site.
- From the third site (770 m), the radar measurement would be equally affected by significant masks for low elevation angles, providing degraded measurements in well marked angular sectors of the Franche-Comté region, and especially over the two north-eastern basins of priority interest (example for VPR 1 in figure 5). This would require a powerful real time data treatment for these sectors, using measurements carried out at higher elevation angles. However, the analysis of the DTM showed that major masked sectors were due to points of the relief located at short distance in the north of the radar position, and additional simulations indicated that these masks could almost completely disappear by moving this site from only a few kilometres.

Finally, these results indicated that none of the three pre-selected sites was very satisfactory. This observation, as well as new constraints of spatial coverage for this future radar, conduced Météo-France to search for a new radar location.

4. HIGHLIGHTED INTERESTING ASPECTS FOR HYDROLOGY

It is interesting to detail some of these results which illustrate the great error variability in space and time of the radar rainfall measurement.

Figure 4 and 5 show maps of the QR ratio obtained with VPR1 (without bright band) for the first and third pre-selected sites of the Franche-Comté radar, and for two elevation angles. A first observation is the drastic decrease of the radar measurement quality with range, in relation with the vertical structure of the radar reflectivity and the increase of the size and altitude of the radar resolution volume with range. This quality decrease is naturally even more dramatic for the higher elevation angle of measurement. Another observation is the very important variability in space of the quality measurement in relation with masks due to relief, and the great difference obtained for the two sites located at short distance (13 km) but at different altitudes. For the lower elevation angle, it is also interesting to note that the mean $\overline{\mathrm{QR}}$ value for the western basin of priority 1 situated at more than 50 km from the radar sites, and outside the zones affected by ground echoes and masks, decreases from 0.86 to 0.73 when the altitude of the radar increases from 770 m to 1050 m. This decrease corresponds to an under-estimation evolving from -14% to -27% for VPR1 even for this small elevation angle. For the 1.4° elevation angle, the mean $\overline{\mathrm{QR}}$ value decrease from 0.56 to 0.31 corresponding to an under-estimation evolving from -44% to -69%.

Many operational observations indicate that the VPR pattern greatly varies in time. Figure 6 presents two maps of the QR ratio obtained for the first site with VPR2 and VPR3, and with the same elevation angle equal to 0.4°. These maps (and the left map of figure 4) show the influence of the VPR variations on the radar measurement quality. The low maximal altitude of precipitation reduces significantly the range of correct radar measurement for VPR2 (compared to others VPR). Also, the low altitude of the bright band for VPR2 results in a detection at short range from the radar, and produces an effect more marked than for VPR3, in spite of a bright band intensity much lower for VPR2. All these effects due to the VPR increase with the elevation angle. Note that for VPR3 and 0.4°, the bright band phenomenon increases the radar reflectivity and maintains the level of the QR ratio close to 1. for distances below 120 km (in operational condition, this phenomenon nevertheless degrades the radar measurement quality).

These results illustrate the importance to treat each source of error in radar measurement with a specific procedure allowing to take into account the spatial and temporal variability of the effects of these errors, and the combination of these effects (for example, the VPR pattern influences the mask values). Such procedures should be used before all comparisons between radar and rain gauge measurements in order to realise more consistent comparisons (or combination). These results also show the great variability of the radar measurement quality for different radar sites located at short distance from each other, and for basins or agglomerations located differently in the same radar coverage, even if they are located at similar distances from the radar. The radar measurement quality can also vary inside the area of interest. In consequence, each utilisation of radar data for an operational application is a particular situation which requires a specific evaluation.

5. CONCLUSION

The objective of the presented studies was to compare *a priori* the capabilities of a number of future radar sites pre-selected by Météo-France for achieving radar rainfall measurement over several basins of priority interest. The discriminating criterion was the estimation of the rainfall measurement quality over these basins, based on the concept of "hydrologic visibility".

The results showed the importance to take into account this type of information (integrating vertical variations of reflectivity) to optimise the choice of a radar location according to the objectives of radar coverage. But they also illustrate the importance to carry out this type of study for existing radars in order to define accurately their hydrologic visibility for different elevation angles, and the spatial and temporal variability of this visibility, in order to improve measurement procedures and data processing.

For a basin or an agglomeration, this type of simulation can bring essential information during the evaluation phase of the radar measurement, before initiating a quantitative utilisation of radar data (in particular to correctly characterise the sources of errors which are most crucial to treat), or before making a comparison (or combination) with rain gauge data. On this subject, the maps of QR ratio indicate the importance to not apply a global adjustment systematically, but to treat before and specifically the spatial variations of the radar measurement errors when it is possible.

Following these operational studies, the initial research software has been optimised to constitute a new VISHYDRO simulation tool easier to use. This simulation tool was used in 2003 to precisely estimate the masks correction factors of two existing radars of the ARAMIS network. Another study aiming to validate QR simulations with long series of volumetric radar and rain gauge data sets is currently in progress at LTHE, and first results are very encouraging. Finally, this simulation tool is presently used in France to estimate the coverage quality of the total ARAMIS network (24 radars in 2006), and to produce models of radar measurement errors for each radar in order to improve operational measurement procedures and data processing in real time (choice of the best elevation angles for volumetric scans, masks correction, optimal combination of data from several radars and several elevation angles).

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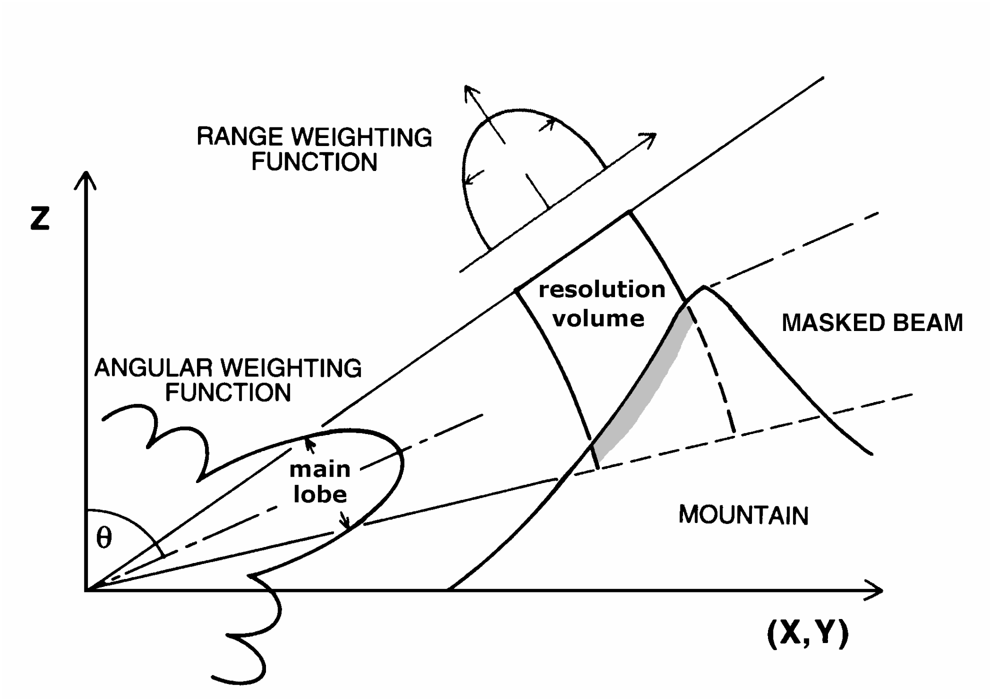


Figure 1 – Description of the radar beam relief interaction: the illuminated area (greyed) is determined by a detailed integration of elementary beam-relief interactions using angular and range weighting functions. The simulation allows to estimate the intensity of ground clutter and the masked part of the beam.

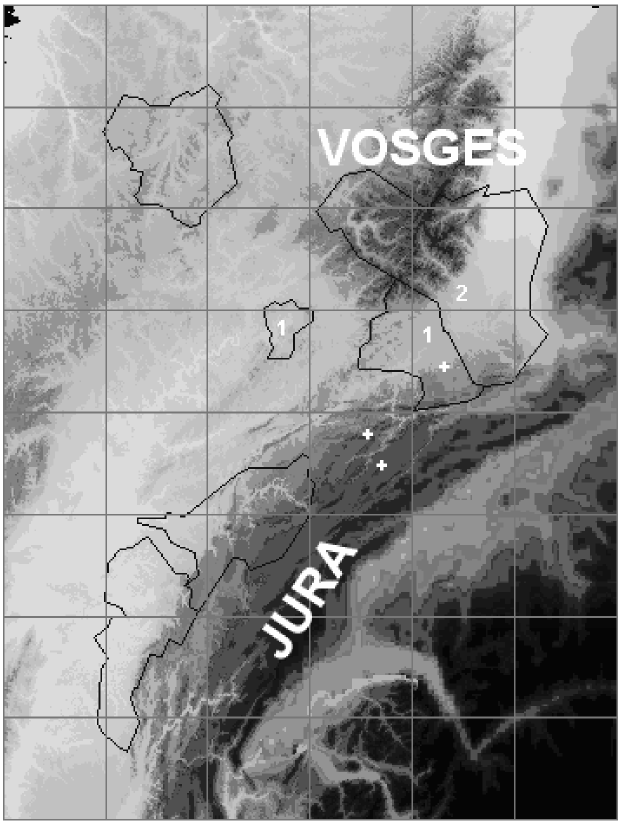


Figure 2 – The Franche-Comté relief (spacing of the grid = 40 km ;
white numbers = basins priority order ; white cross = radar sites).

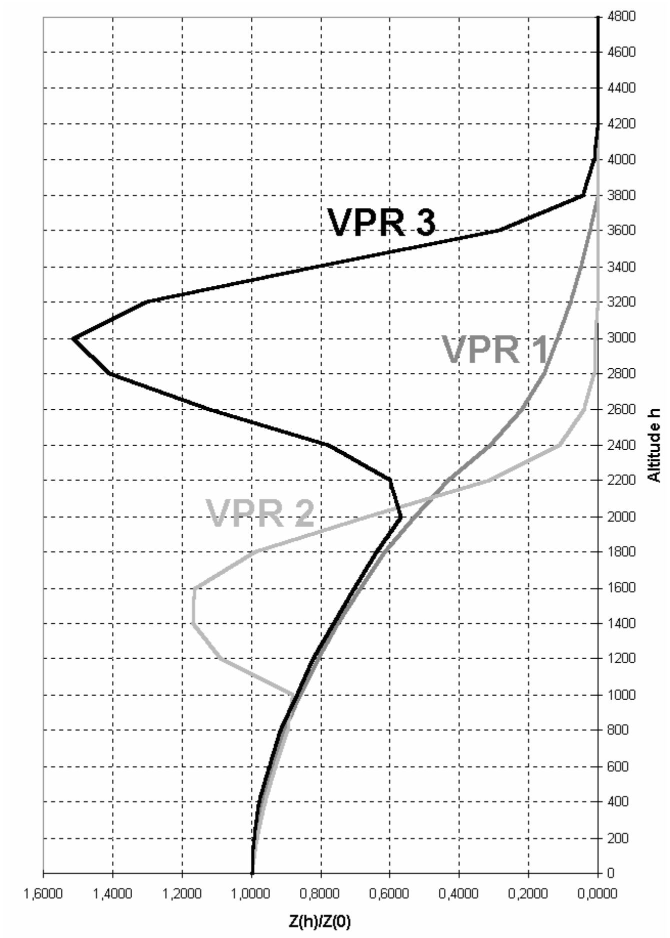
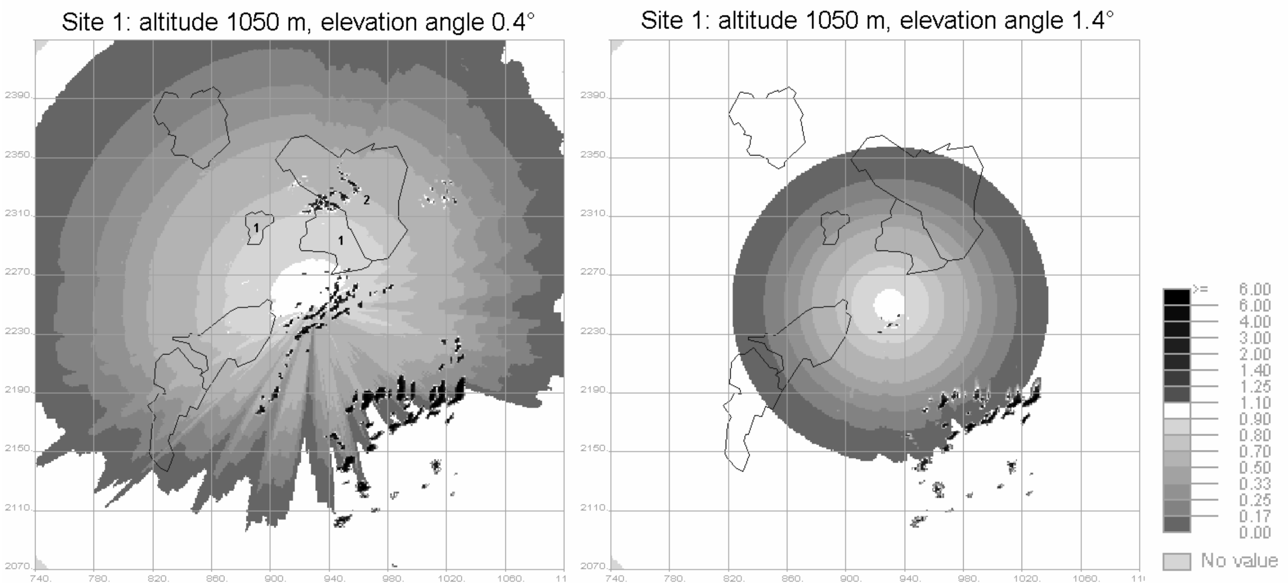
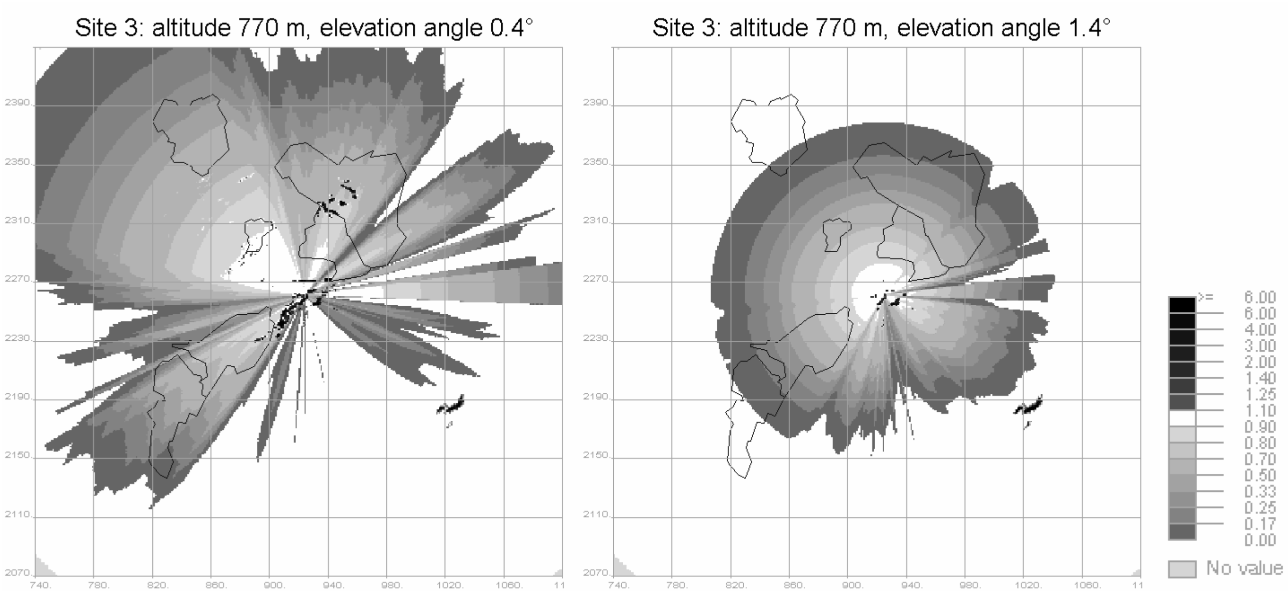


Figure 3 – The Franche-Comté models of VPR : variation of Z(h)/Z(0) in mm^6/m^3.


Site 1: altitude 1050 m, elevation angle 0.4°

Site 1: altitude 1050 m, elevation angle 1.4°

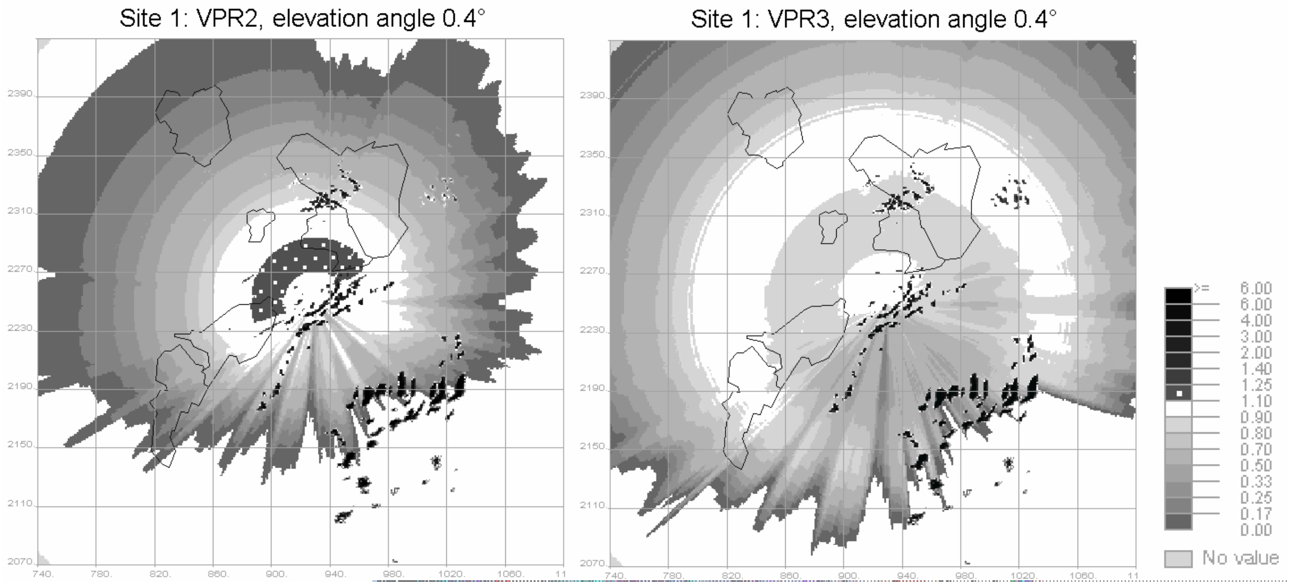
Figure 4 – Values of the QR ratio estimated with VPR1 for ranges varying from 0 to 256 km, and for two elevation angles: 0.4° (left) and 1.4° (right). (spacing of the grid: 40 km ; first radar site of the Franche-Comté region ; black lines: basins of interest ; black numbers = priority order).



Site 3: altitude 770 m, elevation angle 0.4°

Site 3: altitude 770 m, elevation angle 1.4°

Figure 5 – Values of the QR ratio estimated with VPR1 for ranges varying from 0 to 256 km, and for two elevation angles: 0.4° (left) and 1.4° (right). (characteristics similar to figure 2, third radar site).



Site 1: VPR2, elevation angle 0.4°

Site 1: VPR3, elevation angle 0.4°

Figure 6 – Values of the QR ratio for the first site, estimated with VPR2 (left) and VPR3 (right) for ranges varying from 0 to 256 km, and for an elevation angle of 0.4° (Franche-Comté region).