Weather Radar and Abundant Wind Farming – Impacts on Data Quality and Mitigation by Doppler Dual-Polarization

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1 Introduction

Wind energy has been one of the fastest growing energy sources in recent years. The European total power capacity reached 117 GW by February 2014 and it covers about 8% of the electric power consumption in the European Union in normal wind conditions (The European Wind Energy Association, 2014). Significant wind farming infrastructure has been erected consisting of tens of thousands of turbines onshore and offshore in Europe. Desire for higher power capacity drives the technology towards taller turbines with a trend illustrated in Figure 1. For the same reason, the farms are preferably sited at elevated locations, as illustrated in Figure 2. The turbines reach significant heights and they thus show up frequently in the line-of-sights of weather radars.

Due to the large quantity of these moving targets, interfering effects are unavoidable in the observations of weather radar networks. At the level of managing the observational infrastructure, the potential impact mechanisms have been identified (OPERA, 2010, Vogt et al 2011). When a farm is in the radar line-of-sight, echoes of wind turbines tend show up as clutter in the fields of reflectivity used for detecting and estimating precipitation. At the same time, the quality of Doppler information and of dual-polarization measurands of meteorological echo may deteriorate when in overlap with turbine echo. When located within a few kilometers from the radar, turbine structures may block radar signals in the sectors occupied by the farm facility and the observations are hence affected throughout the range of the radar. Radar hardware and personnel may become at risk if these major infrastructures are co-located. Fortunately, extreme cases are rare and these advanced technologies can co-exist as soon as reasonable minimal site separations are respected (OPERA 2010, Vogt et al 2011). Presuming these general guide lines, attention turns into the follow up of co-habitation and into mitigation of the residual effects in view of optimized radar data quality. A number of studies on the impacts of wind farms and of research towards mitigation methodologies have been reported, recently (Bobillot G et al, 2012; Lorandel R., 2012; Marcellin J.-P., 2012; Sempere-Torres D, 2011; Sempere-Torres D, 2012).

The Galician Weather Service, MeteoGalicia, has been operating a C-band dual-polarization radar since 2010 in an environment of dense wind farming. A public compilation of wind farming activity in Galicia suggests for more than 4000 wind turbines (TheWindPower, 2014). Further farms exist within the radar range beyond the Galicia borders. MeteoGalicia broadcasts results from meteorological surveillance scans as well as products characterizing precipitation types and quantitative estimates of accumulated rain fall, in near-real-time (MeteoGalicia, 2014). Months of archived data are available to the great public, too. Consistent quality of observations is obviously a mandatory element in successful dissemination of this kind. Quality builds on the long-term management of infrastructure including the site environment, and on best operational practices which utilize the standard capabilities of the Vaisala WRM200 radar hardware and software (Vaisala, 2014). The data resource thus represents a realistic benchmarking of operational data quality, including the specific aspects of wind farming. The bench mark is of general interest because the operations are based on reproducible elements such as the recommendations agreed in the weather radar community (OPERA, 2010) and the commercially available radar hardware and software.

Our study comprises of the following steps. First, we describe the key features of radar operations at MeteoGalicia. We brief out the signal and data processing methodologies in use. We describe how the wind farm locations are monitored as an element of infrastructure management. We describe distinct simple features in wind farm echoes of dual-polarization Doppler weather radar which are found useful monitoring find farm locations. The knowledge of the wind farm locations allows us to characterize the echo from wind farms located at various distances. We describe the methodology of operstional quality control. We investigate quality of reflectivity fields used as input to the estimates of 6-hour rain fall accumulation used as the main bench mark of the data quality. We look for quantified expressions of requirements for reliable rain fall accumulations at locations of wind farms.

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Figure 1: Size evolution of wind turbines over time. Source: European Wind Energy Association.

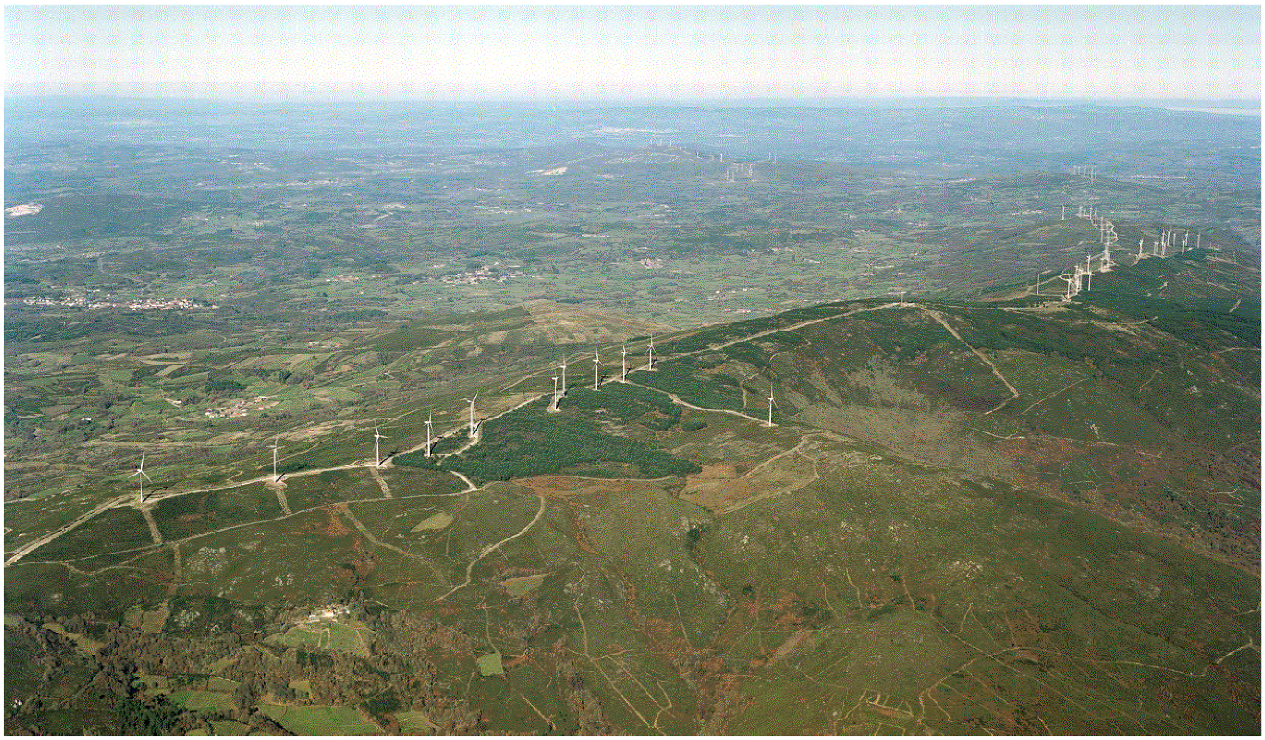

Figure 2: View at the Faro Farelo wind farm in Galicia, Spain, representing typical preferred onshore sites in the region.

2 The WRM200 dual-polarization Doppler weather radar at MeteoGalicia

The WRM200 weather radar of MeteoGalicia is located at the Valga site on a hill at the altitude of 700 m, approximately. The site has a favorable radar horizon into all directions. The nearest mountain tops at altitudes in excess of 1000 m are about 30 km into South-East, and mountain tops in excess of 1000 m can be found at the Eastern and Southern borders of Galicia. The orography of the region is displayed in Figure 3.

In conditions of fair weather, the Valga radar operates in the surveillance mode in which simple volume scans are repeated every ten minutes, covering the ranges up to 350 km. As soon as precipitation signal is observed in excess of 9 dBZ within the range of 200 km, the radar scheduler is swapped to the precipitation mode, in which a hybrid volume scan consisting of eight elevations is repeated every five minutes covering ranges up to 250 km, interleaved by the surveillance sweeps up to 280 km every ten minutes. The basic system parameters of the WRM200 radar are summarized in Table 1.

Observations from the surveillance mode and from the precipitation mode are used in public products. The methods and algorithms of IRIS™ weather software are used to compute base products as well as advanced products such as rainfall intensities accumulated up to 6 hours. The data quality are managed by the radar signal and data processing, and no data quality are generally necessary in post-processing. Observations are constrained to cover the area of Galicia and near ocean waters. In disseminating the rainfall products, the scale setting cuts off the accumulations less than 0.1 mm in 6 hours.

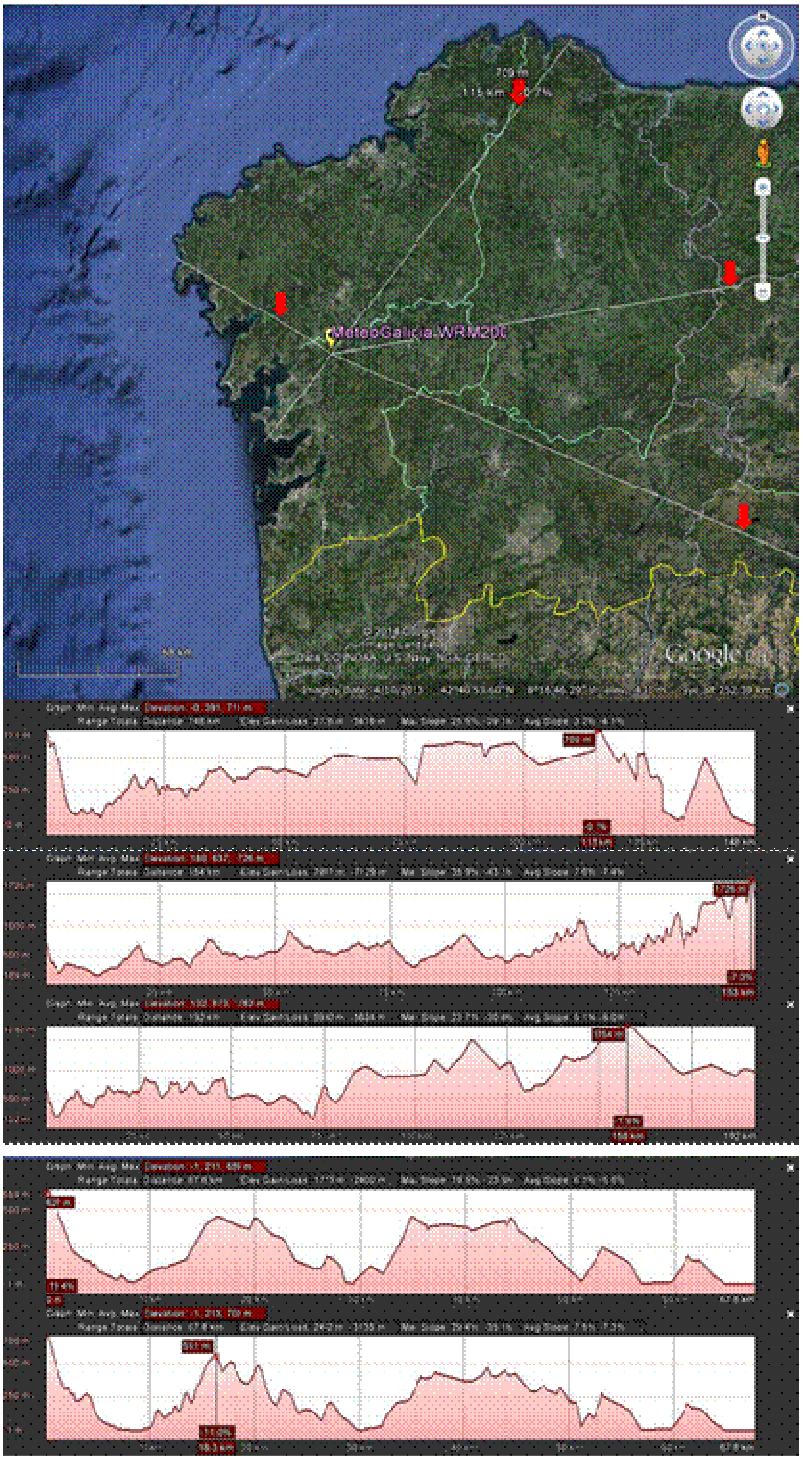

Figure 3: Orography in Galicia. The path profiles are projected into North-East, East, South-East, South-West and North-West.

Table 1. WRM200 radar system parameters

Transmitter		***Antenna***	
Tyype	Magnetron	*Type*	Center-fed parabolic reflector
Operating frequency	5.5-5.7 Ghz	*Diameter*	4.5 m
Peak power	250kW	*Gain (typical)*	45 dB
Pulse width	0.5, 0.8, 1.0, 2.0 µs	*Beam width*	<1 degree
PRF	200 to 2400 Hz	*Peak side lobes on axis (typical)*	-33 dB
RF-to-IF receiver		***Pedestal***	
Type	Dual stage, dual channel IF downconverter	*Type*	Semi yoke elevation over azimuth
Dynamic range	> 99 dB (2 µs pulse)	*Elevation range*	-2 to 108 degrees
IF frequency	442/60 MHz	*Maximum scan rate*	40 deg/sec
Noise figure	< 2 dB	*Position accuracy*	Better than 0.1 deg
Signal processor type		VAISALA SIGMET RVP8 (8.13.3)	
Radar operations and data processing		VAISALA SIGMET IRIS (8.13.3)	

3 Mapping the wind farms in the line-of-sight of Doppler dual-polarization weather radar

Follow-up of wind farming status is a non-trivial task in the phase of build-up and in early operations. Actual operational status may vary. Details of the available information may be incomplete or inaccurate. MeteoGalicia has compiled a dedicated collection of the operational wind farms with co-ordinate information at the level of individual turbines, in the region of Galicia. An accurate data base of turbine locations is a vital element in understanding their effects in presence of other significant phenomena such as ground clutter, urban clutter and other man-made interferences.

The collection is based on three cross-checked sources of information. The regional energy administration of Galicia (INEGA, Instituto Enerxético de Galicia) provides digital maps of the farm sites as well as of the individual turbine locations. Geographic high resolution imagery such as GoogleEarth is able to display individual turbines. They can be recognized due to their significant size and specific pattern. Most of the GoogleEarth imagery of Galicia dates to 2012 or later, which is sufficiently up-to-date to map all the currently installed wind farms within Galicia. WRM200 receives radar echo from turbines as soon as they are in the radar line-of-sight. In favorable conditions, the locations wind farms can be recognized in the radar observations, using simple signatures described in Subsection 3.1. The typical radar spatial resolution of a few hundred meters is sufficient for determining the candidate locations in which the individual turbines can be identified and located in GoogleEarth. The confirmed turbines have been stored as flag lists in GoogleEarth.

The Valga radar site is favorable and the radar line-of-sight reaches into most parts of Galicia within the range of 150 km. When combined with the preferred elevated locations of wind farms, radar echoes are observed from candidate sites corresponding to about 3000 individual wind turbines, tagged and confirmed in the high resolution imagery. Additional 600 turbines have been relocated in the municipal data base, confirmed in the high resolution imagery. The data base thus contains more than 3600 visually confirmed wind turbines within Galicia. The wind farm data base of MeteoGalicia is illustrated in Figure 4.

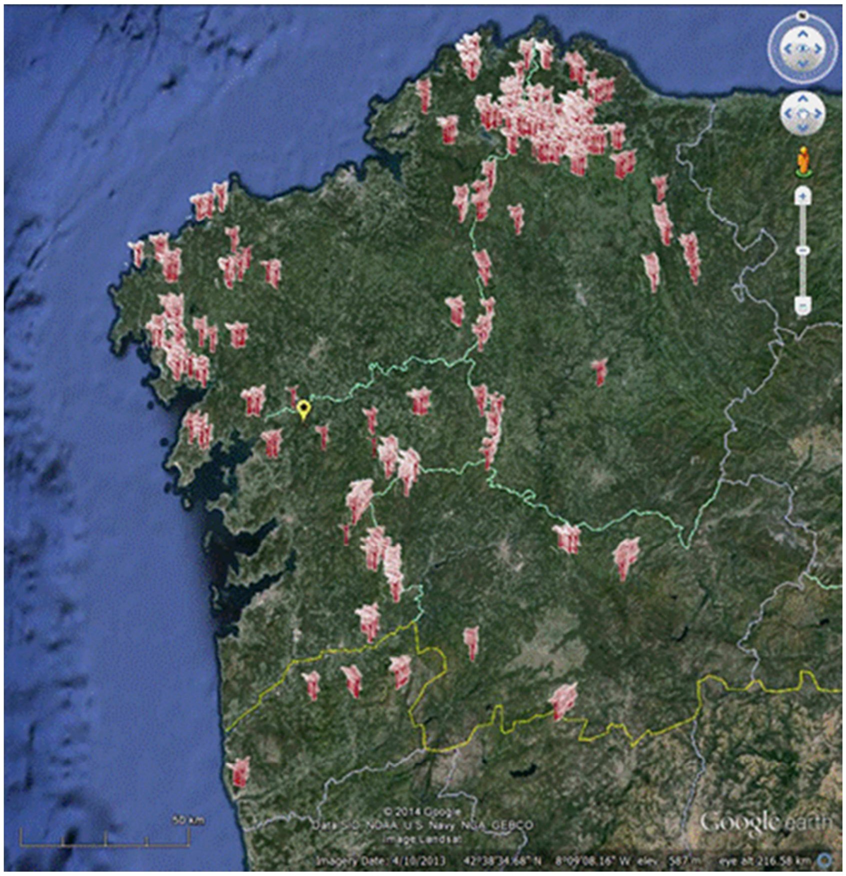

Figure 4: The collection of verified wind turbine sites in the region of Galicia, as of the summer 2014.

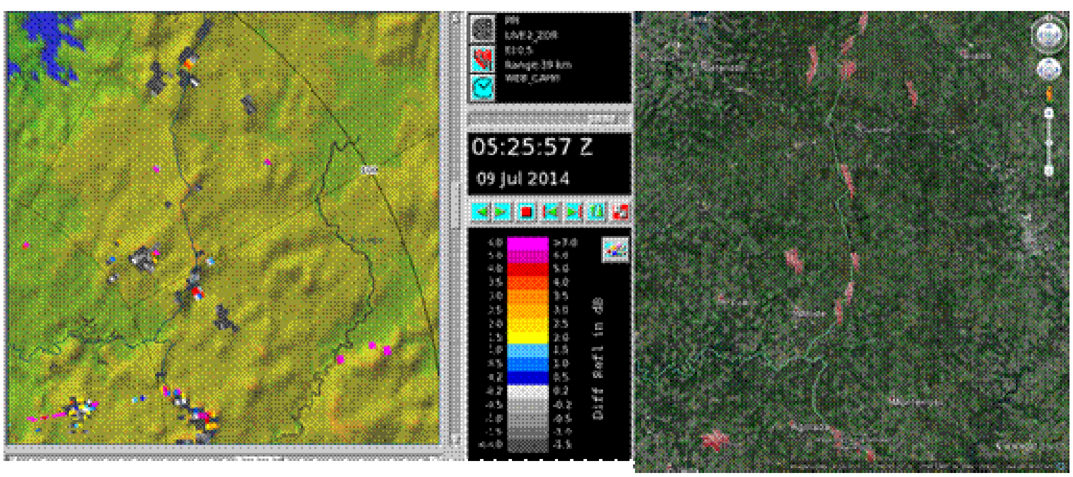

Figure 5: Recognition of wind farm locations by the Valga WRM200 radar. On the left, the fields of Doppler filtered differential reflectivity. They are censored at P/N=1.2 dB. The bins of negative differential reflectivity associate closely with the locations of wind turbines visualized on the right. An exception relates with an active construction site of other type. The turbine locations are obtained from independent data base and they have been verified in the GoogleEarth imagery,

3.1 Radar based interactive recognition of wind farms based on dual-polarization signatures of wind farming

Empirically, dual-polarization radar echoes of wind farms appear distinct. The farm locations can be efficiently recognized through visual inspection from samples of dual-polarization data acquired in favorable conditions. The conditions are favorable when precipitation echo is absent and bio-scatter contamination is low ("fair weather and clear air"), for example in early morning hours.

In particular, the fields of differential reflectivity (Z_{dr}) are sensitive to wind farm locations, when Z_{dr} is computed from moments filtered for static ground clutter and the Z_{dr} fields are censored for thermal noise so that the rate of noise speckle is low. In favorable clear air conditions, data are dominated by moving targets. Additionally, the wind farm echoes appear to be associated with significantly negative values of Z_{dr}. This feature is persistent and differentiates the wind farm echo from the residual other type echo, as shown in Figure 5.

We do not have the firm explanation for the preference for negative Z_{dr} values in turbine echo while it may relate with the rotating turbines blades which reflect echo passing Doppler filtering. Despite the fact that the rotating blades are randomly oriented in average in the system of horizontal and vertical polarization planes, vertically oriented blades may have a preference in the echo because they reach higher into the radar beam.

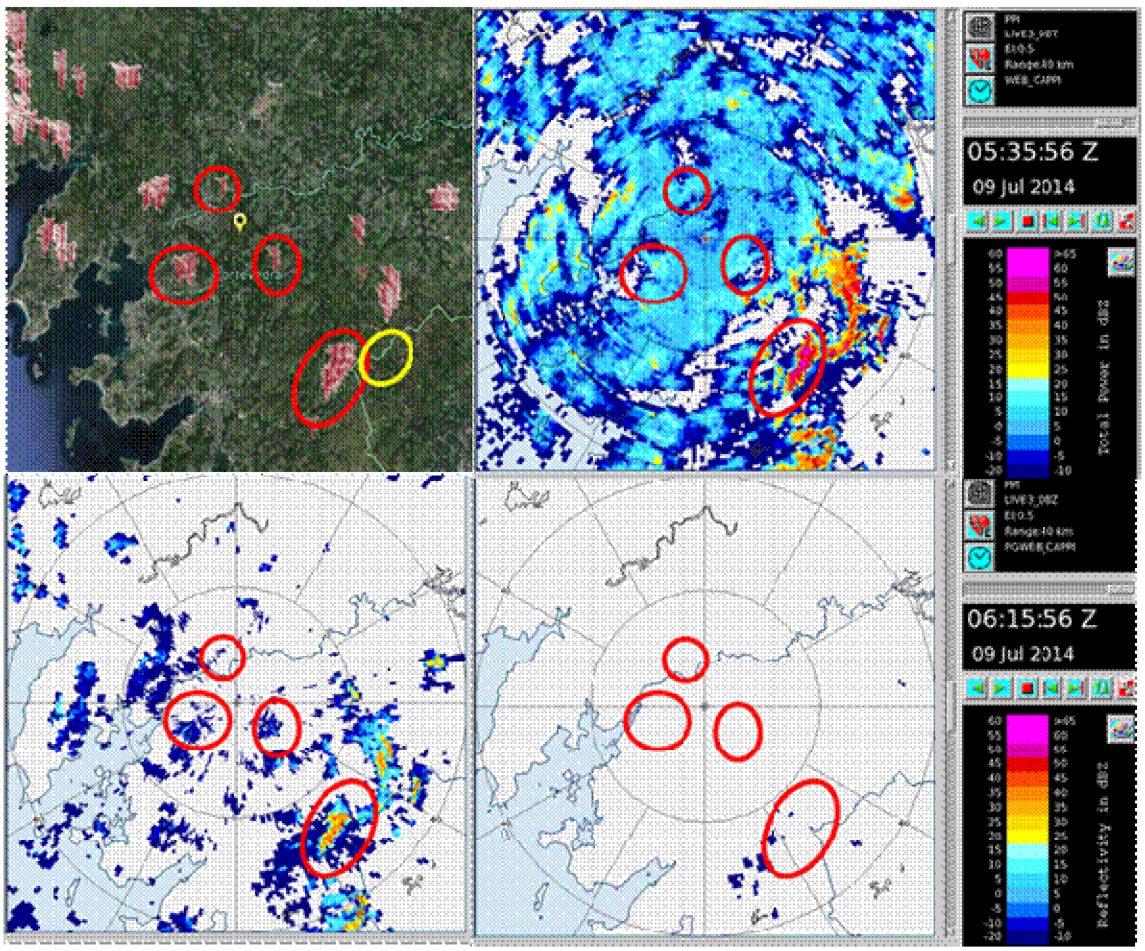

Figure 6: a) the location of verified wind turbines within the range of 40 km from the Valga radar. Red ovals indicate the sites of echo evaluation. The yellow oval marks the reference hill without turbines (plain ground echo). b) Fields of total echo in units of dBZ observed at the Valga radar. c) Fields of Doppler filtered reflectivity. In b) and c) LOG censoring is applied at P/N=1.2 dB. d) Fields of reflectivity after all the quality considerations, see Section 5.

4 Strengths of static and moving clutter from locations of wind farms

We have evaluated the strengths of total echo and of the residual echo after Doppler filtering from wind farm locations selected in Table 1 and displayed in Figures 6a and 7a. We consider the wind farms closest to the Valga radar at distances of 7 to 9 km, the extreme echo from farm locations at the distance of 28 km from the radar at high hills into the South-East, as well as the wide area of wind farming at distances more than 100 km into North-East. As a reference, we also consider a hill top at the distance of 31 km, without a wind farm.

Strong echoes are received from wind farms located in higher altitudes, as shown in Figures 6b and 7b. Significant component of static ground clutter can be inferred from orography i.e. ground clutter echo would be present even if the farms were absent. Static parts of the turbines add to the ground echo.

Static ground clutter can be suppressed through Doppler filtering of the Gaussian Model Adaptive Processing (GMAP, 2005) in the IRIS/RDA™ dual-polarization signal processing. The filtered moments recover the underlying signal which may be significantly weaker than the clutter power. A conceptual limit of ground clutter suppression approaches 60 dB, while levels of 30 dB can be targeted operationally. Indeed, this materializes at the Valga radar, as indicated by the level of residual filtered echo from the selected plain hill target, in Figures 6c and 7c.

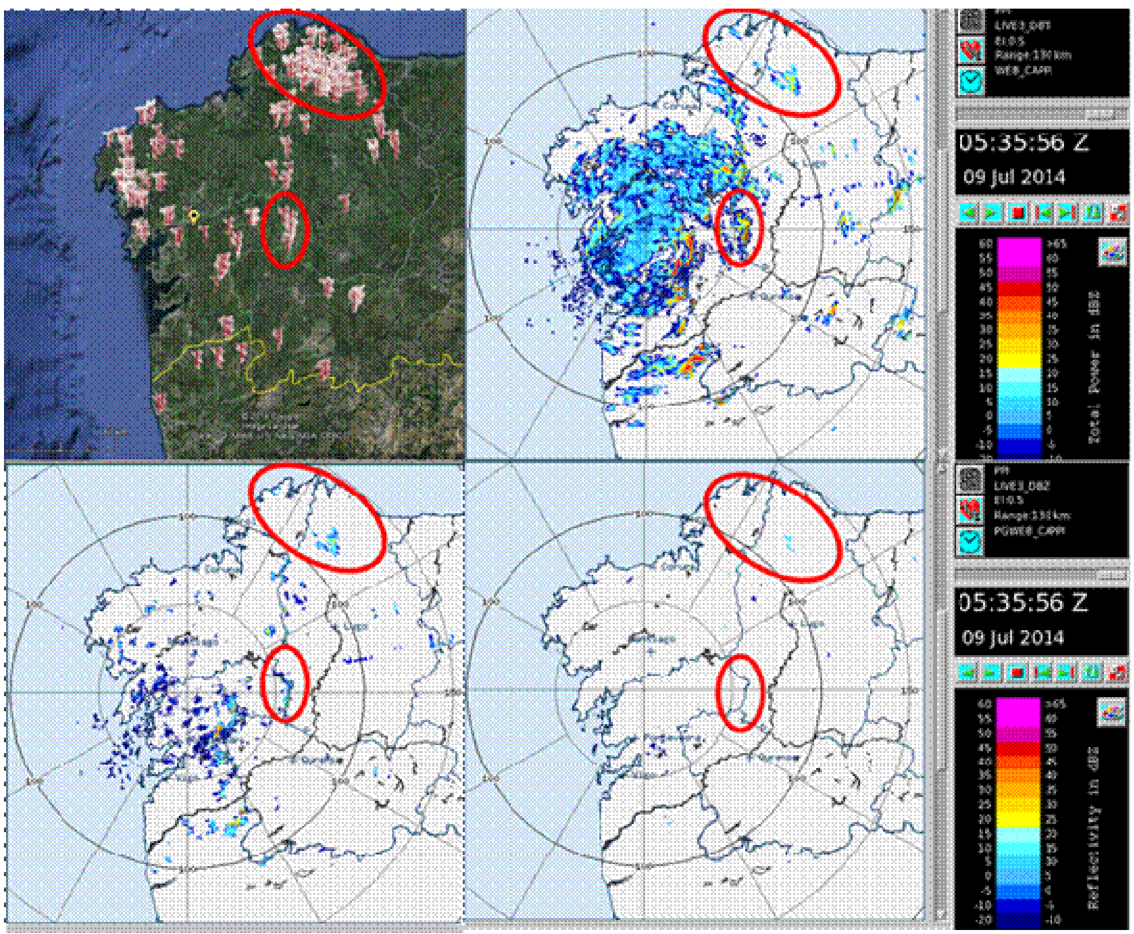

Figure 7; as Figure 6 but up to radar ranges of 150 km.

The echo levels from the selected locations are presented graphically in Figure 8 in units of dBZ. Thanks to the favorable Valga radar site at top of the highest hill within 25 km, the total echoes from the nearest wind farms are moderate because they effectively stay under the radar beam. In contrast, the echoes exceed 50 dBZ from the farm locations at the altitude of 1 km into the East and South-East. The clutter is strong from the reference location without wind turbines, too. Numerous wind farms are in the line-of-sight of the Valga radar at the hills at the distances more than 100 km into North-East, while the farms located in the slopes into the sea or at the coast stripe (see Figure 4) do not contribute to the clutter observed at the Valga radar. Beam broadening is a factor in observations at these distances. We estimate that the Valga radar receives echoes from about 3000 wind turbines within Galicia. The typical echo strengths from unevaluated sites vary from background noise up to 30 dBZ.

Doppler filtering removes essentially all the weaker ground clutter and suppresses the strongest ground targets at clutter-to-signal-ratios (CSR) of 30 dB or more. Nevertheless, static clutter alone remains the limiting factor for observing reflectivities below 20 dBZ in the areas where strongest echo may well exceed 50 dBZ. The clutter at wind farm locations is hardly mitigated by more than 10 dB, as shown in Figure 8. This suggests for nonnegligible moving clutter underlying the dominant ground clutter. The “flash” effects may be present in the filtered echo, while the analysis is too coarse to confirm their existence or properties.

Table 2. The wind farm and hill sites selected for dedicated echo analysis

Farm location LAT/LON (dgr)	Bearing (dgr)	Range from radar (km)	Altitude (m)	Average echo (dBZ)	Echo max/min (dBZ)
42.6469/-8.5161	122.	7.3	530	16	19/13
42.6339/-8.6964	244.0	9.7	500	23	29/12
42.7561/-8.6246	338.9	9.1	370	12	17/9
42.4756/-8.3815	142.9	27.8	950	54	56/51
42.6201/-7.9002	96.0	56.5	1000	50	53/49
43.4006/-7.5584	45.7	116.1	900	24	31/18
Hill location					
42.5089/-8.2875	127.0	30.7	800	58.0	63/53

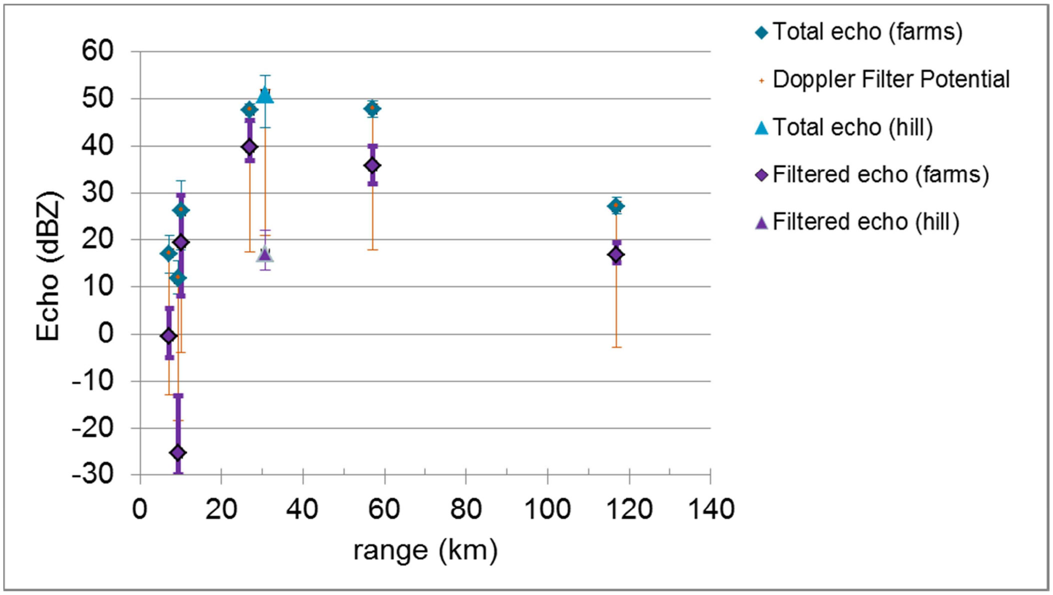

Figure 8: Representation of the echo power levels from the target locations selected in Table 1. The blue symbols indicate the total echo in units of dBZ. The violet symbols indicate the echo levels after Doppler filtering (GMAP).The blue error bars indicate the variability in ten consecutive sweeps. The yellow bar indicates the generic capability for ground clutter suppression 30 dB which is realized for plain hill echo in a sweep of antenna, while the echo is reduced less when from wind farms.

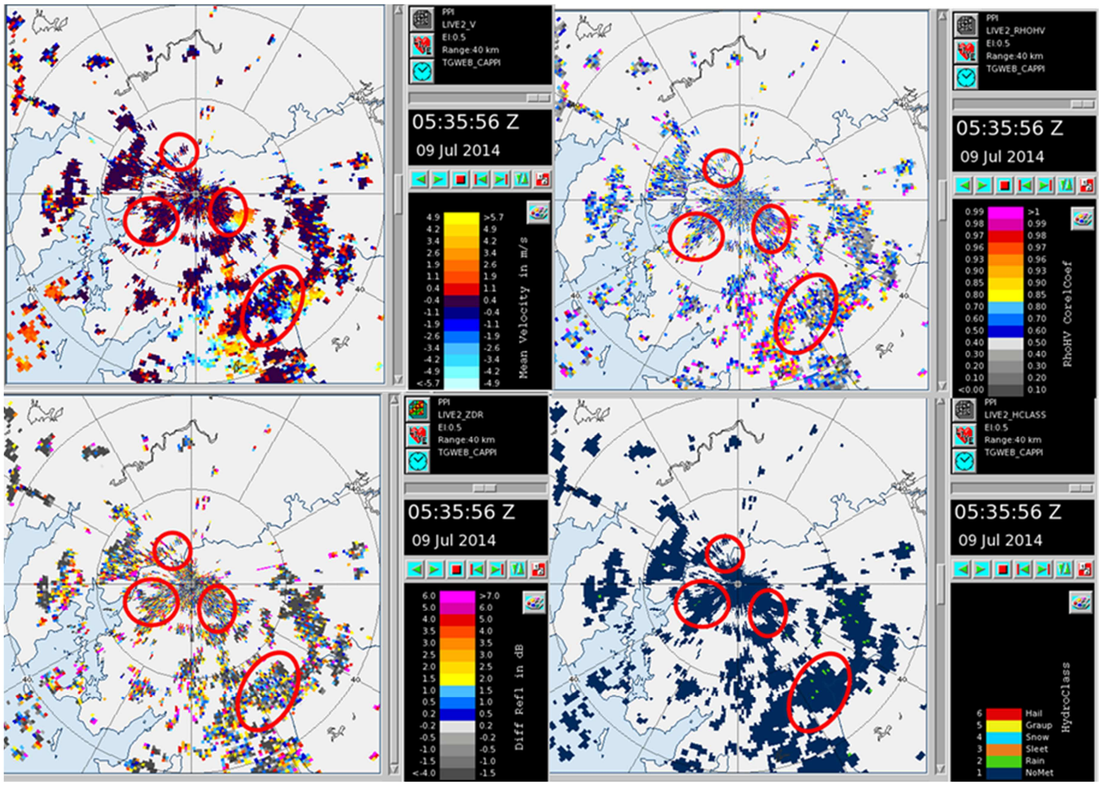

Figure 9: Fields of a) Doppler radial velocity, b) co-polar coefficient, c) differential reflectivity and d) HydroClass classifications. Up to the ranges of 40 km.

5 Mitigation of wind turbines with general purpose Doppler dual-polarization quality methods

It is well known that dual-polarization Doppler radar is able to differentiate non-meteorological echo from precipitation signals The general capability has been mounted in IRIS/RDA™ signal processing for quality control purposes (Chanthavong V. et al, 2010). In its current form, gate data can be censored by the configurable criterion of Polarimetric Meteorological Index (PMI) which considers the rule strengths of ‘precipitation’ versus those of ‘non-meteorological’ computed by the fuzzy methods in HydroClass™ (Keränen et al, 2008). Originally, ‘non-meteorological’ was defined to consist of ground clutter and bio-scatter, while it has turned out efficient in distinguishing many kind of echoes of non-Rayleigh scattering, which display reduced correlation and/or power imbalance between the signals in H and V polarization channels, as well as of irregular spatial patterns (Chanthavong et al, 2010).

Obviously, wind farm echoes resemble the characteristics of ‘non meteorological echo’ as shown in Figure 9 for ranges less than 30 km, where they resemble ground clutter. At longer ranges, the characteristics are more variable, as shown in Figure 10 up to the range of 130 km. The rule strengths of HydroClass™ thus tend to prefer wind farms as non-meteorological. This information can be utilized by applying the PMI quality criterion to the radar moment data, in companion with other quality criteria such as LOG (on signal-to-noise), SQI (on Doppler coherence) and CSR (on ground clutter-to-signal ratio).

Additional standard RDA algorithms of point clutter and micro-clutter suppression are applied as parts of high performance Doppler filters. They consider spatial smoothness of base moments at the highest internal spatial resolution i.e. before the typical ray level steps of range averaging are taken. As a recommended setting, digital filters for man-made radio frequency interferences are used, too. Furthermore, filters are applied for isolated ‘speckle’ remaining after LOG, SQI, CSR and PMI censoring of the moment data.

When these general purpose quality tools are applied in combination, the residual clutter from wind farms is suppressed significantly, as shown in Figures 6d) up to ranges of 40 km and in Figure 7d) up to ranges of 150 km. As expected, the performance of dual-polarization identification varies as a function range, while the combined functionality is robust up to the distances where farm echo could persist. It is to be noted that these methods are applied essentially in their default settings (the factory values of the WRM200 delivery). Their scope is not limited to wind farm clutter, but they serve as comprehensive quality control of precipitation data in the environment of ‘modern clutter’ which often consist of several natural and man-made sources.

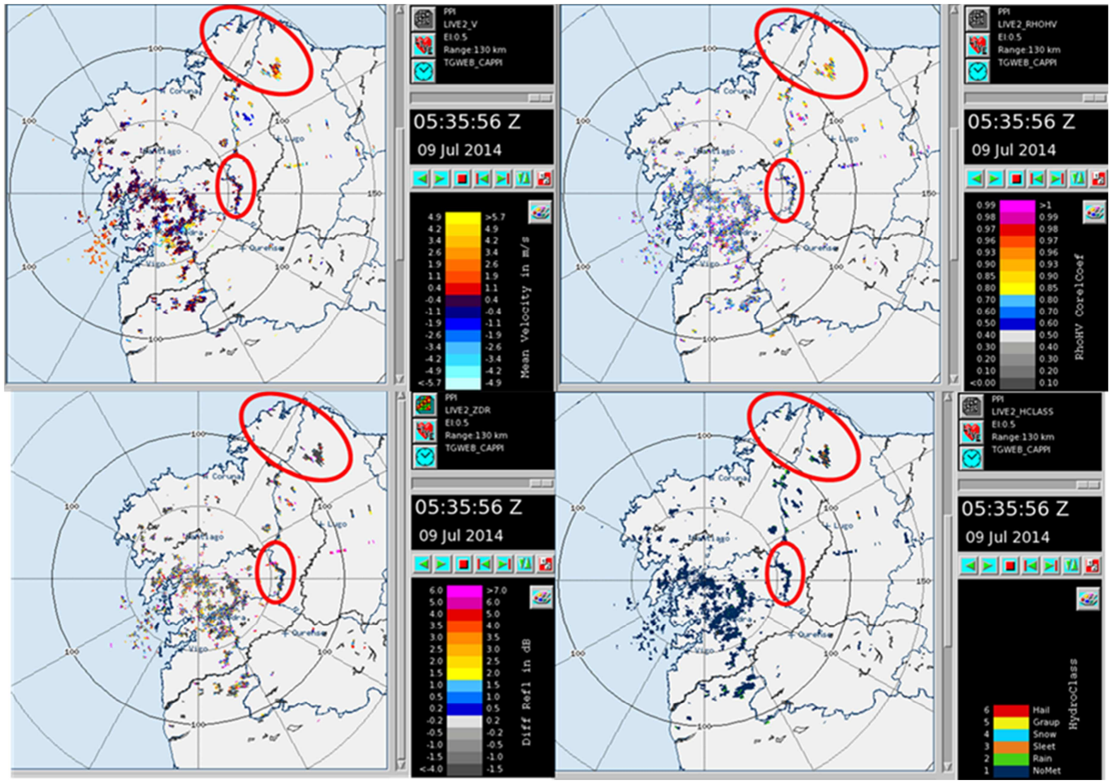

Figure 10: Fields of a) Doppler radial velocity, b) co-polar coefficient, c) differential reflectivity and d) HydroClass classifications, up to the ranges of 130 km.

5.1 Precipitation signals overlapping the wind farm clutter

Given the visible mitigation of wind turbine clutter in conditions of fair weather leading to reduction of false precipitation signals, we are keen to learn to which degree precipitation signals are accepted (or rejected) when received from the regions of wind farm locations. We evaluate this through inspections of weather cases of wide spread precipitation as well as of localized showers.

We consider large scale precipitation passing through the area of the order of 100 km^2 in the North-East occupied by up to 1000 turbines. The region and the typical fields of clear air echo are displayed in Figure 11. The farms in the left half of the area are partly blocked by orography, while the farms in the right half reflect intense echo. Figure 12 visualize how precipitation passes through the dense area of wind turbines. The precipitation signals are essentially observed in all details with marginal loss of observations for reflectivity values below 5 dBZ, approximately. This level is significantly lower than the strongest total unfiltered echo in excess of 25 dBZ from find farms in the area considered, see Figure 7. The level is about 10 dB above the minimal precipitation signal which could be detected if the underlying background was ideal thermal noise.

We understand the consistency of this outcome with our evaluations in Section 4, as follows. The quoted maximal echoes are not persistent, not even in the location of most intense echo. Flashing is a known mechanism, and the farm echoes are unevenly distributed in space and in time. The typical farm clutter level is thus less than 25 dBZ. From Section 4, we learn that Doppler filtering suppresses the static part of the echo from wind farm location (structures or ground) by about 10 dB. We note that the fuzzy criteria of HydroClass are adjusted for robust and high efficiency identification of precipitation. Contributions of precipitation signals in the gates of the clutter and in the neighboring gates tend to improve the odds for accepting the gate as precipitation. Finally, the gap fill part of speckle filtering restores precipitation in individual bins of clutter, in case a fair fraction of the surrounding gates are precipitation. The synthesis of these quality considerations contributes to the *robustness* of processing to such a significant degree that signals as low as a few dBZ are correctly identified in wide spread precipitation.

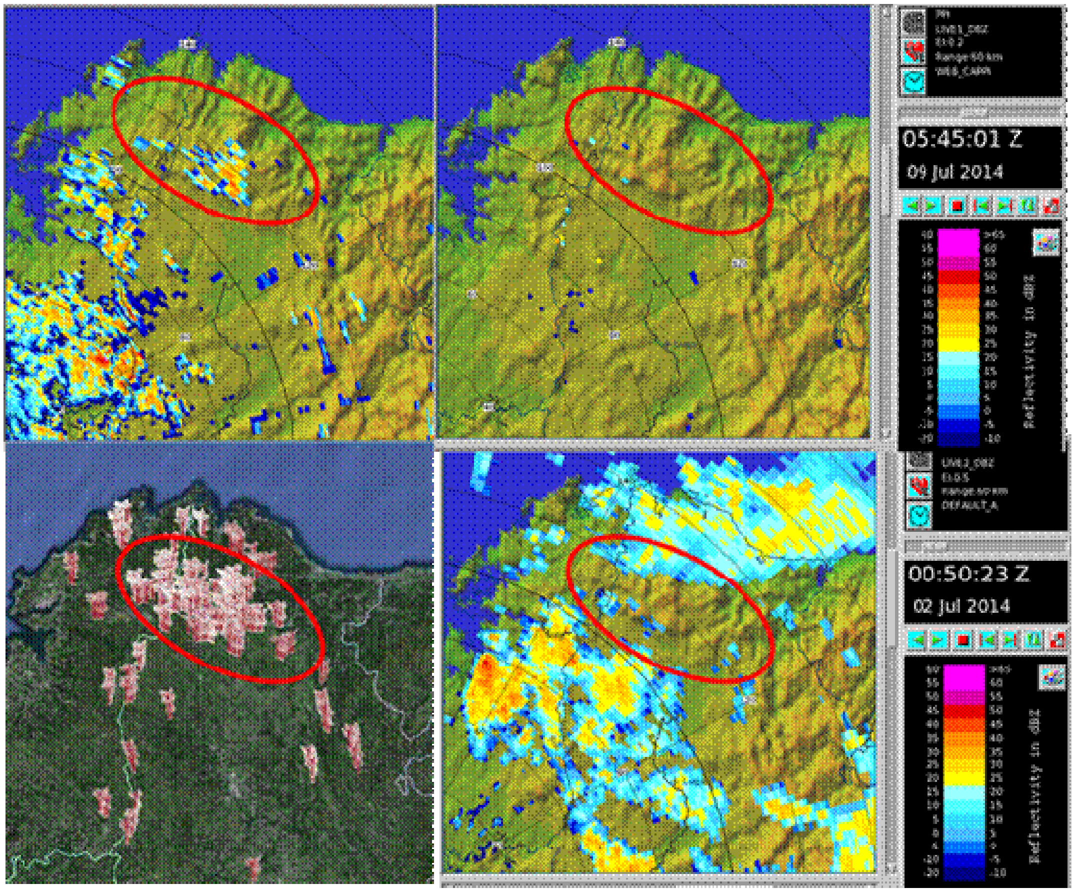

Figure 11: A region of dense wind farming. a) total echo, b) field of Doppler filtered reflectivity subject quality considerations in clear air conditions, see text. c) locations of wind farms, and d) field of Doppler filtered reflectivity subject quality considerations in wide spread precipitation, approaching the area of dense farming. See next Figure.

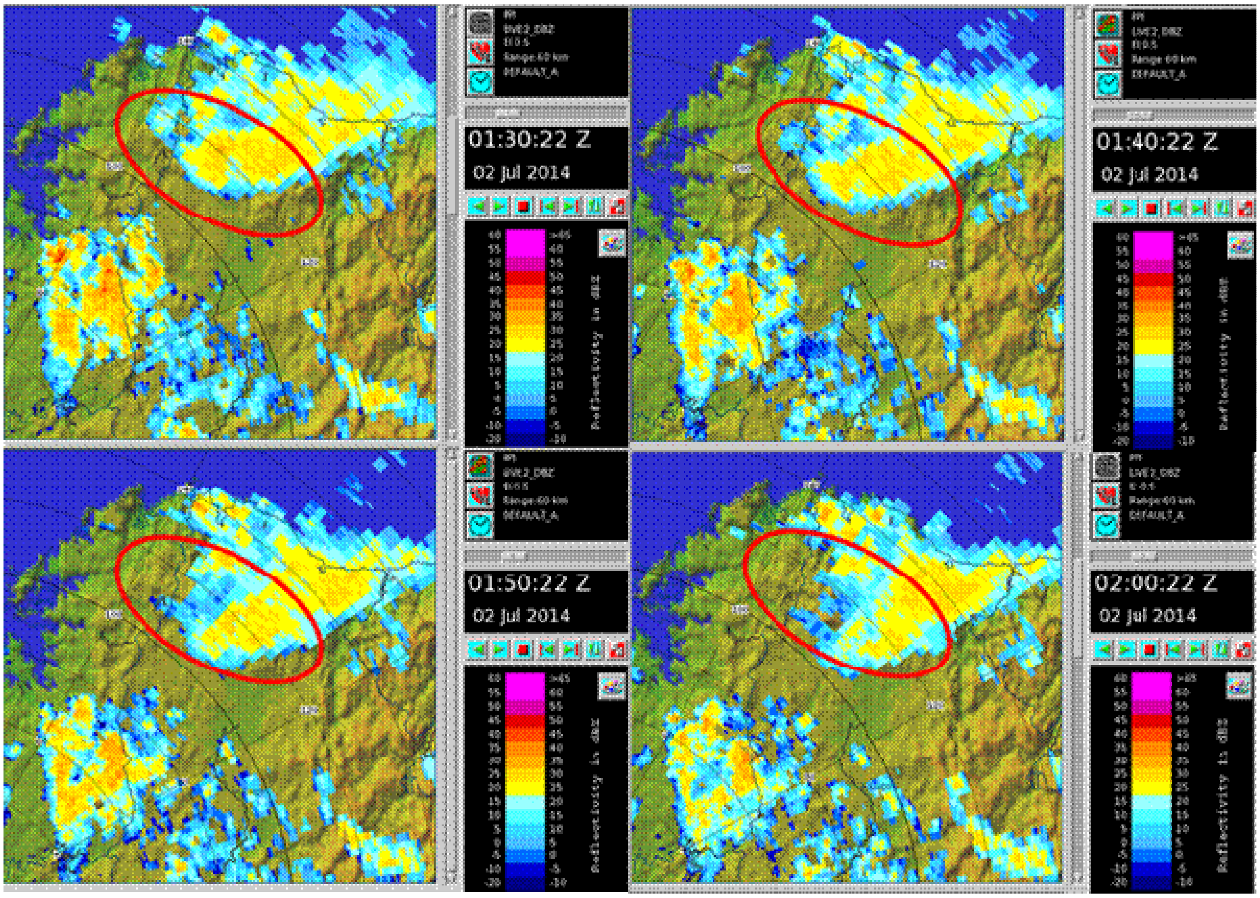

Figure 12: Passage of large scale precipitation in the area occupied by a large number of wind turbines, see Figure 11.

We recognize the quality criteria utilize spatial smoothness of precipitation as a feature differentiating it from clutter. Small scale precipitation is then at risk of recognition. We evaluate this by inspecting localized showers passing through the area of clusters of wind farms, some 30 km North West from the Valga radar. We select the area in which echoes are not saturated by the static ground clutter while numerous sources of moving clutter are visible. The region and the typical fields of clear air echo are displayed in Figure 13. We find out that localized showers of a few square kilometers can be observed uninterrupted when passing through the location of farms, as soon as their size exceeds the spatial resolution of gates in range and in azimuth. The spatial considerations typically consider the nearest gates, namely. The fuzzy criteria may consider larger gate intervals, but they are adaptive and robust so that localized precipitation is accounted for in the method construct. Echo may be lost in individual gates or even in clusters of bin clusters, momentarily, while the echo is recovered in subsequent sweeps at the same location. Actual temporal evolution of convection is a relevant mechanism which calls for frequent scans, any case. An example of a successful reconstruction of precipitation shower on top of a wind farm is displayed in Figure 14.

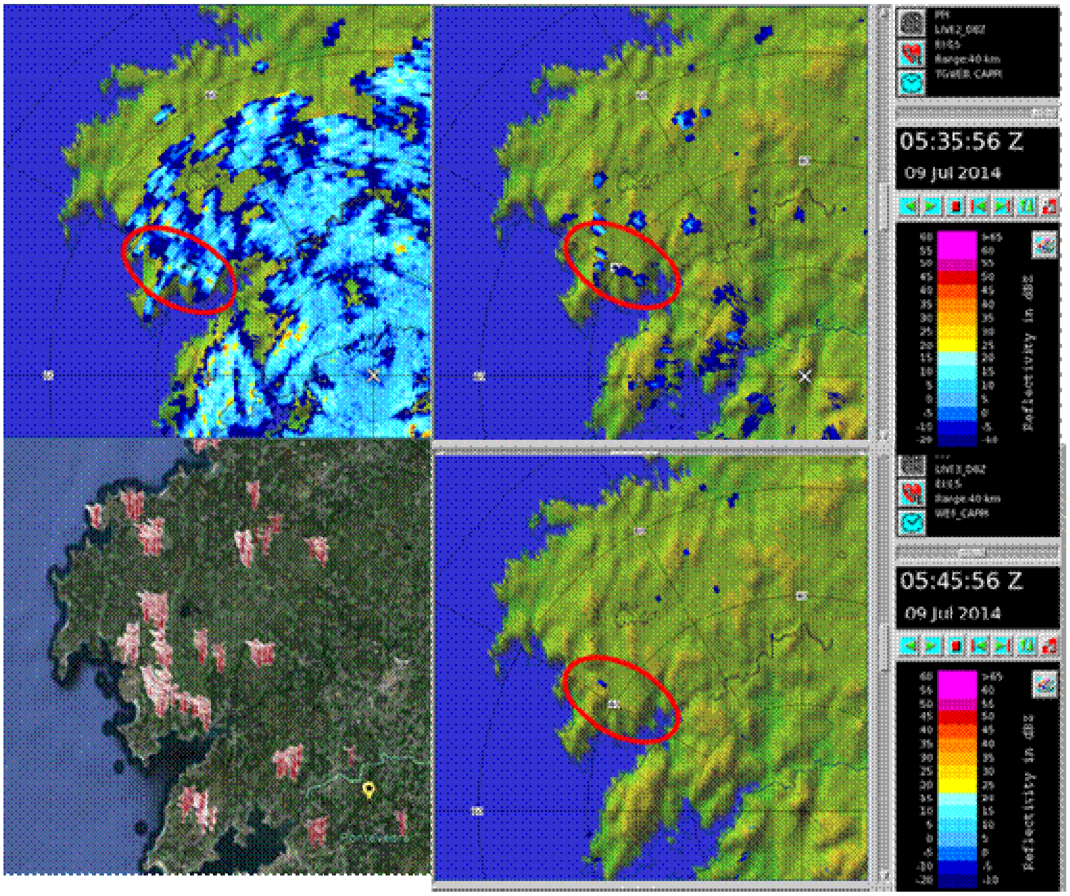

Figure13: A region of wind farm clusters. a) total echo, b) field of Doppler filtered reflectivity subject quality considerations in clear air conditions, see text. c) locations of wind farms, and d) field of Doppler filtered reflectivity subject quality considerations in wide spread precipitation, see text.

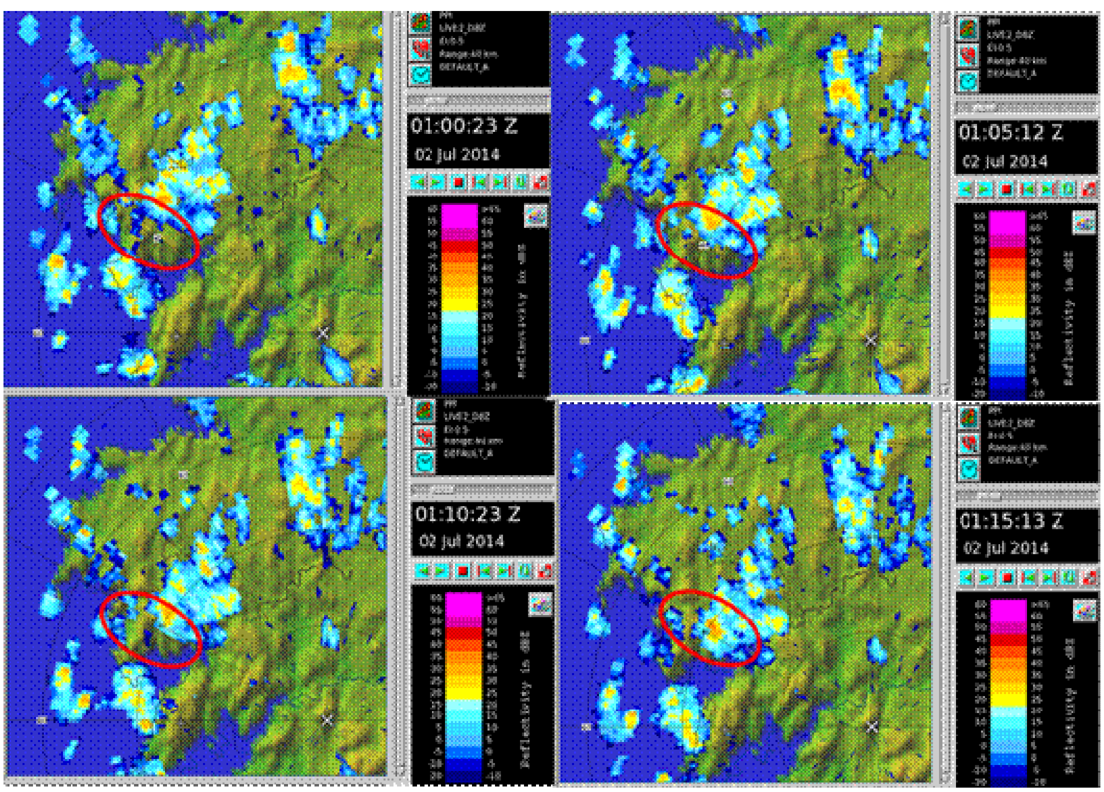

Figure 14: An example case of a localized precipitation shower passing through a wind farm, see Figure 14.

6 Quality of rain fall accumulations

Since October 2012, MeteoGalicia has successfully applied PMI censoring as well as the other quality considerations discussed in Section 5, on the fields of reflectivity used for public products such as weather surveillance, precipitation type and estimates of six hour rain fall accumulations, see (MeteoGalicia, 2014). Generally, the quality of the products meets the needs of dissemination to non-expert users. The information can be interpreted without references to explanations or disclaimers of exceptional features.

The estimates of rain fall accumulations are obtained from the fields of reflectivity observed by the Valga radar and computed as the IRIS RAINN products. Accumulations are computed at the spatial resolution of 0.5x0.5 km^2 . The Marshall-Palmer R(Z) relation is used. No post-processing is applied but the public display scale defines a lower limit of reported accumulation corresponding to 0.1 mm of rain fall in six hours. This is a low value from view point of hydrology. We recall the rain fall intensity of 0.1 mm/hr is sometimes used as the boundary value between rain and drizzle. The six hour accumulations are summed from momentary estimates of surface rainfall intensity (SRI) estimated from fields of reflectivity in volume scans repeated every five minutes. Consequently, one spike signal of about 27 dBZ translates into a visible low entry in the public six hour accumulation product. False alarms of these type of echo should thus be kept at the frequency level of 10^{-2} per gate in order keep public products rigorous. A persistent echo at 27 dBZ At the same time, persistent entries of reflectivity should be kept below 1 dBZ in order to avoid any visible accumulation in six hours.

Figure 15 displays a typical accumulation of six hours of rain fall computed from the reflectivity scans in the precipitation mode while fair weather dominates the regions of interest, broad cast on the January 31st 2014 (06-12 UTC). Generally, the reported rain fall accumulations are negligible. Most of the farm locations within the radar line-of-sight correctly report no precipitation at all. One can recognize the impact of wind farms as entries associated with a subset of farm locations. The reported values are in the range from 0.01 to 0.5 mm accumulation in six hours. The level of 0.5 mm accumulation would result from spikes of 27 dBZ at five per cent false alarm rate, or alternatively from persistent clutter of about 10 dBZ. Actual contamination is likely a mixture of these two extremes. We infer that the residual persistent wind farm clutter is confined to a level below 10 dBZ, and at the same time occurrence of spikes in excess of 25 dBZ are suppressed to a level of a few per cent – even in the most challenging locations. Most of the locations are suppressed to levels well below this. Contributions of static clutter are all absent.

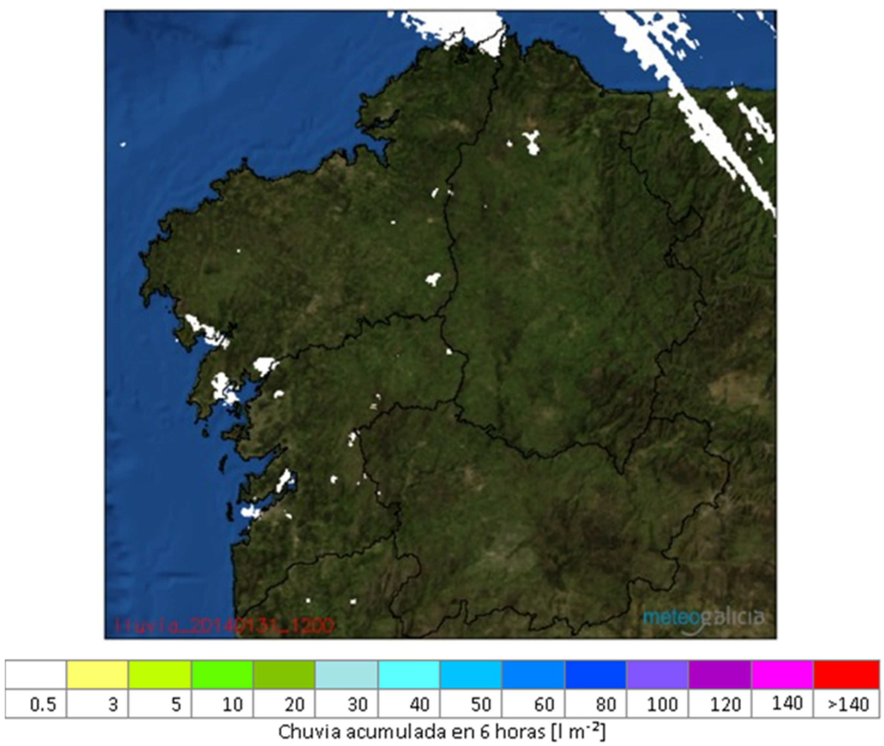

Figure 15: the public report of six hours of rain fall accumulation on the January 31st (06-12 UTC) computed from the reflectivity scans in the precipitation mode while fair weather dominates most of the onshore area within Galicia.

Figure 16 displays the accumulation of six hours of rain fall from area of precipitation which spread into Galicia on January 31st, 2014 (12-18 UTC). The case is selected as an interval in which rain fall covered the interesting areas of numerous wind farms, summing up smoothly to a nearly constant low level in the range 0.1 to 0.5 mm in six hours. The case thus serves as a simple and efficient bench mark to spot any gaps which may arise due to beam blockage or erroneous rejection of precipitation signal in signal and data processing. When compared with the known locations of wind farms, the field of reported rain fall accumulation is nearly perfect. In particular, observations are homogenous in the wide area of dense deployment of turbines into North-East (see Figure 11 and the related analysis). No gaps nor anomalous spikes can be associated with the known locations of wind farms. Gaps in observations at the range of 30 km into South-East may relate with blockage by orography, naturally or combined with wind farms on top of the hills (see Figure 6). Vanishing accumulation in the South could be the truth in the temporal and spatial coverage of precipitation, or a combined effect of orography and beam overshooting in the cool season.

We conclude significant consistency with the findings in Section 6 that the fields of reflectivity are correctly recognized as precipitation in all locations of wind farms, as soon as they reach the level of 5 dBZ and the level of static ground clutter allows their estimation. These types of observations are routinely reported into public, available in the data archive (MeteoGalicia, 2014).

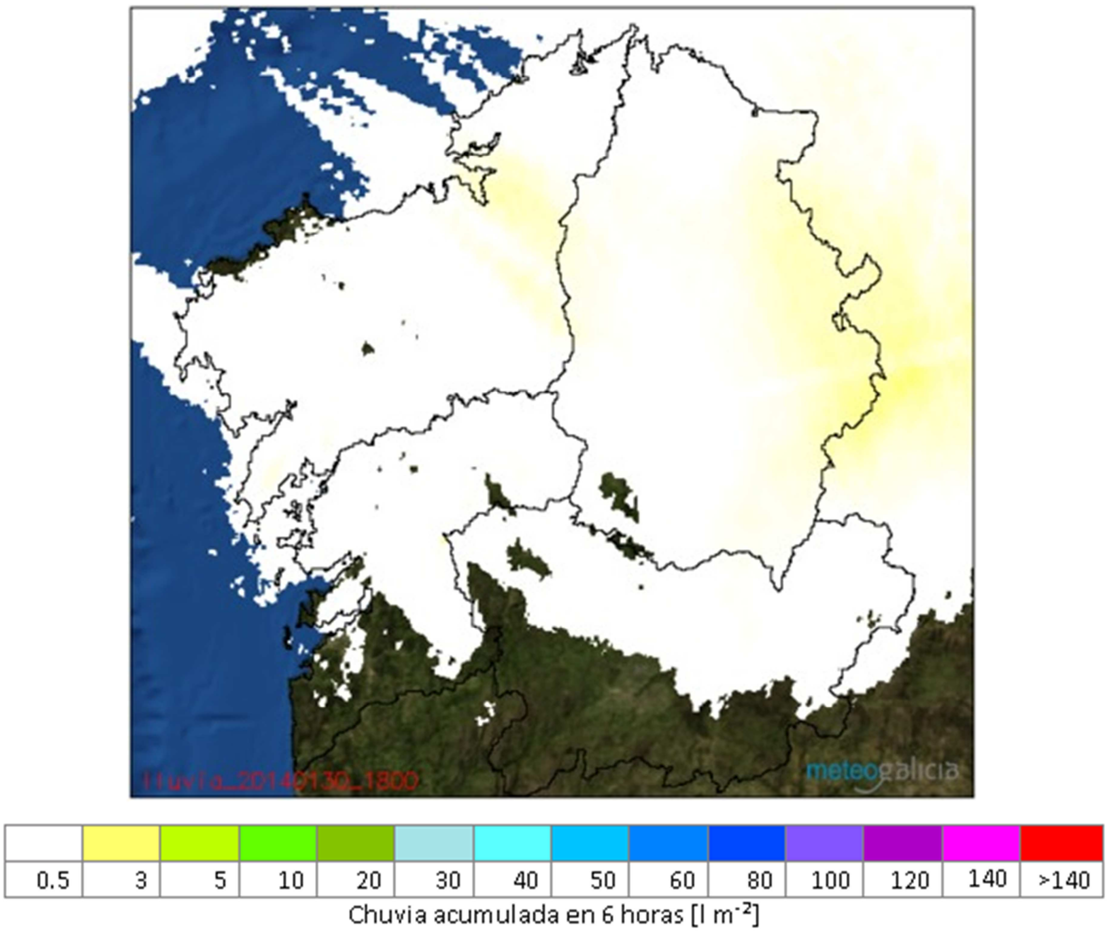

Figure 156: the public report of six hours of rain fall accumulation on the January 31st (12-18 UTC) computed from the reflectivity scans when precipitation passes through Galicia from North towards South.

7 Conclusions and Summary

General assessment of weather radar data quality in presence of wind farming is a broad topic. In this study, we have focused on the fields of reflectivity taken as primary radar observations, in particular on the false signals of precipitation due wind farm clutter and on the potential gaps in spatial coverage which may be generated as a trade-off in mitigating the clutter.

Quality of observations such as reflectivity, Doppler velocity or the dual-polarization measurands depends on their interpretation and utilization. For example, we have found dual-polarization information very qualified for identifying wind farm locations and for mitigating the wind farm clutter as an element of the general purpose data quality criteria. This trivially implies that dual-polarization signals of precipitation are affected when from locations of wind farms, perhaps significantly. Interpretations of those data as precision measurements of the overlying precipitation call for specific attention and potentially actions. These are not covered here. Similarly, we have not attempted quantifying the measurement errors in reflectivity due flashing or blockage. Tools are available while unused for systematic corrections for mean bias by blockages.

Extensive wind farming is a significant source of clutter seen by the Valga radar. Unless blocked by orography, wind farms may generate significant clutter at distances beyond 100 km. Without mitigation, the persistent wind farm clutter may contaminate rain fall estimates at the level of tens of mm rendering them useless for most purposes. In the general scope, relative altitudes of the wind turbines with respect to the radar site should be recognized relevant parameters in the approval process of wind farm sites (the simplest measure of line-of-sight, in essence).

Wind farm clutter co-exists with other sources of clutter, of which the ground echo often dominates in specific locations of the elevated orography, even in the favorable characteristics of the Valga site. Filtering of static ground echo is thus a vital prerequisite in wind farm mitigation. In fact, the implications of natural orography should not be confused with those of wind farming, for example when beam blockage and clutter cancellation capability are considered.

Signals of wind farm echo are distinct in observations Doppler dual-polarization weather radar. In conditions of clear air, wind farm locations can be recognized, essentially unambiguously, in the fields of Doppler filtered reflectivity when censored against thermal noise and associated with observations of negative values of differential reflectivity. The signature is simple enough to be used efficiently in interactive monitoring and in validation of operational wind farms. Accurate information of wind farm locations is an essential asset in understanding the radar data quality in presence of wind farming.

The adverse impacts of wind farming are visible mitigated in the fields of reflectivity observed by the Valga radar, used as the base input to public weather products. The methodology has been in use since October 2012 and it has proven robust. High quality radar hardware and software, the site quality, as well as the best operational practices are the enabling factors in the success. The methodology is a synthesis of the legacy of quality tools of Doppler weather radar and of the advanced echo identification capability of dual-polarization. Apart from wind farm clutter, the approach manages multiple issues in observational data simultaneously - it is a general purpose solution to the task of quality control of radar observations of precipitation. The solution utilizes the recommended policies for wind farm sites and is based on standard elements of the WRM200 radar system.

Detailed evaluations of the fields of reflectivity in conditions of fair weather and of wide spread precipitation suggest that signals of wide spread precipitation are correctly recognized as soon as their strength reaches 5 dBZ, approximately. Rain fall accumulations as low as 0.5 mm can be routinely reported at wind farm locations. At distances of 130 km this is about 10 dB above the WRM200 detectability of precipitation, in conditions of plain thermal background. Holes and excess signals are negligible when comparison of continuity is made to neighboring locations of no farming. No dramatic trade-off is observed in recognition of small scale precipitation. The case study outcomes are confirmed by the long term follow up of the estimates of six hour accumulations of rain fall reported to public. In conditions of negligible precipitation, the residual wind farm clutter corresponds to rain fall accumulations well below 0.5 mm in six hours, even in the most challenging conditions of Galicia where about 3000 turbines are in line-of-sight to the Valga radar, alone.

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