WIND TURBINES SEEN IN RADAR DATA WITH THE BIG DIFFERENCE METHOD

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1 Introduction

The effectiveness of filtering wind turbines in radar data is degraded by the moving rotor blades. Therefore, the echoes of wind turbines may remain visible in radar images of precipitation. The degree of disturbance by the wind turbines is not really clear in a given setting. It is argued that the radar data are affected even far away from the wind turbines, due to multi-body scattering and side-lobe effects of the radar antenna (DWD 2013a). For these reasons, the users of radar data, especially weather services, are concerned about the growing number of wind turbines in the vicinity of radar stations. Based on a recommendation by (WMO 2010), the German Weather Service does not allow the construction of wind turbines closer than 5 km to a radar site (DWD 2013b). In the range 5-15 km from a radar the construction of wind turbines is only allowed as long as the peaks of the rotor blades remain below the altitude of the radar antenna. These restrictions inhibit the plans of manufacturers of wind turbines, since the economic benefits of big turbines are better than those of smaller ones.

In that conflict, there is a need for a better understanding of the effects of wind turbines on radar data. Studies of these effects are typically done with multi-year data samples (Norin, 2015), (Teschl, et al., 2016), in order to isolate the effects of the wind turbines in probability distributions of the quantities of interest, e.g., radar reflectivity (Z, dBZ) or Doppler velocity (V, m/s). The main reason for the need of long-term radar data is the natural variability of these quantities.

In this contribution, we investigate the differences of Z (dB) and V (m/s), measured in two plan position indicators (PPI's) at adjacent elevation angles. The echoes of precipitation show small differences in a proper setting (short distance from the radar, short time lag between the radar measurements, no melting layer, smooth radar patterns, negligible advection), but the differences increase dramatically under the influence of wind turbines and other sources of clutter. So, using proper threshold values applied to the measured differences lead to an objective detection of the areas affected by wind turbines. The dramatic advantage of this method is that much shorter time series of radar data than used in the studies mentioned above are required for a quantitative assessment of the effects of wind turbines on radar data.

We use in this study the radar data of a 12 hour period in early summer 2017, measured with the radar Türkheim in Southern Germany. This period covers dry weather and a cluster of thunderstorms followed by stratiform precipitation. Four wind turbines are in a distance of 2.5 km from the radar. A communication tower (the "tower" hereafter) is, not far away, in the same distance from the radar as the wind turbines. We investigate the differences of Z and V in various sectors: in free air above shadowed ground, above visible ground, at the locations of the tower and the wind turbines and in various distances from these obstacles. We found that each sector has its characteristic "footprint": a characteristic percentage number of big differences as a function of precipitation intensity. We show and discuss hereafter some examples for illustration and summarize our findings on how the effects of wind turbines depend on distance from the turbines.

2 Data and procedure

The radar Türkheim is located in a complex relief, composed of flat hills, steep valleys, free fields, forests and a variety of mostly small settlements. About 10 wind farms can be found within a distance of 15 km from the radar. For this study, we have selected the wind farm Aufhausen, consisting of 4 wind turbines in a distance of about 2.5 km from the radar. A tower is located a bit north of the turbines. Fig. 1 shows the positions of the turbines, the tower and the radar.

The radar operates continuously, providing 11 PPI scans of radar reflectivity Z (dBZ) and Doppler velocity V (m/s) every 5 min. We analyze the PPI data at the elevation angles 0.5, 1.5, 2.5 and 3.5 deg. The differences DZ and DV are defined in Equations (1) and (2), the indices *up* and *lo* correspond to these pairs of elevation angles: 1.5/0.5, 2.5/1.5 and 3.5/2.5 deg.

$$DZ = Z_{up} - Z_{lo}(dB) \qquad (1)$$

$$DV = V_{up} - V_{lo}(m/s) \qquad (2)$$

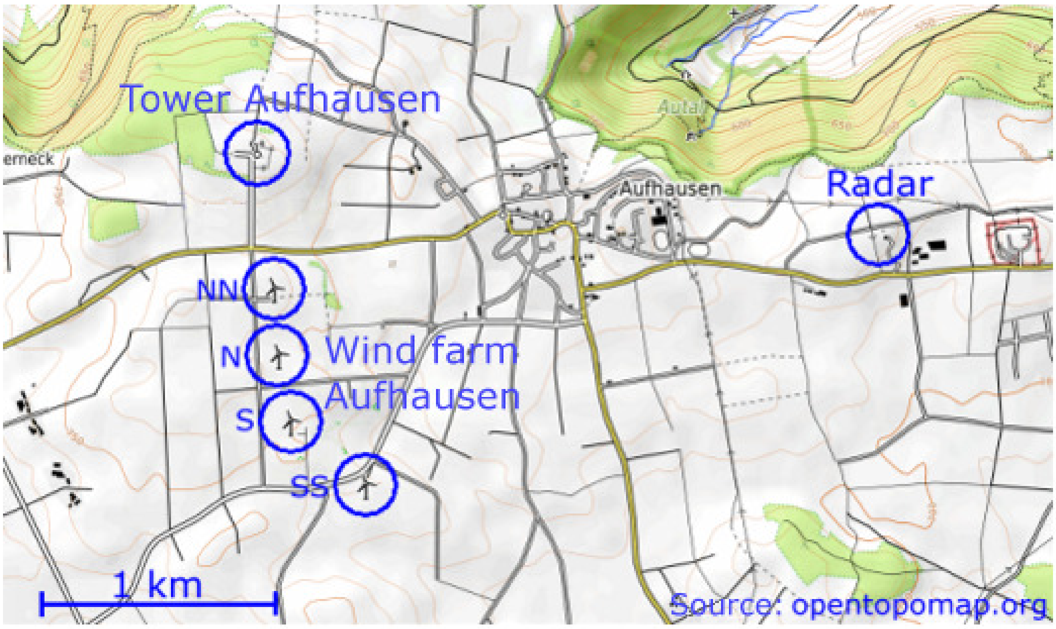

Fig. 1: The radar, the wind turbines and a communication tower nearby.

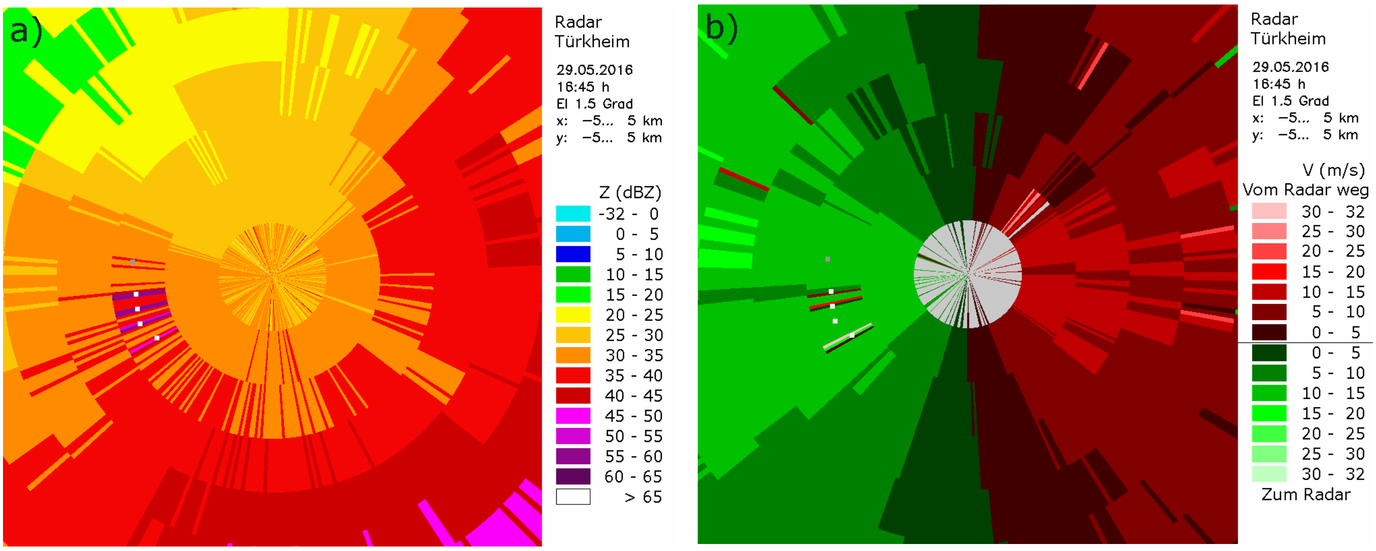

Fig. 2: Radar reflectivity (a) and Doppler velocity (b) at 16:45 UTC on 29 May 2016

The radar data cover a time period of 12 hours (1000-2200 UTC on 29 May 2016) and have a resolution of 1 km in range and 1 deg. in azimuth. The data passed a clutter filter based on Doppler criteria (DWD 2013a) but they did not pass the new quality management system called RADOLAN (DWD 2017). This system includes an improved filtering of radar data based on polarisation criteria. We recently obtained the same data but optimized with RADOLAN, but the time to consider these data here was too short. Fig. 2 illustrates the effects of the wind turbines on the radar data. The reflectivity pattern (Fig. 2a) shows higher values at the locations of the wind turbines (white dots) than elsewhere. The Doppler velocities (Fig. 2b) are affected as well, but one can find isolated erroneous values of Doppler velocity also far away from the wind turbines.

We define various sectors of interest, typically composed of a couple of neighboring radar pixels. Fig. 3 gives an overview of the sectors in the vicinity of the wind turbines and the tower. The **core sectors** are defined by three neighboring radar pixels in azimuthal direction, surrounding one obstacle. In addition, we define four **neighboring sectors**, two of them on the left and right side of a core sector, and two of them on the back side, seen from the radar. We also define sectors far away from any towers, above shadowed terrain and above visible terrain when viewed from the radar. For brevity, we do not show the locations of these sectors here. The sector above shadowed terrain is called the **clean sector** hereafter, it is assumed that this sector is not affected by ground clutter echoes.

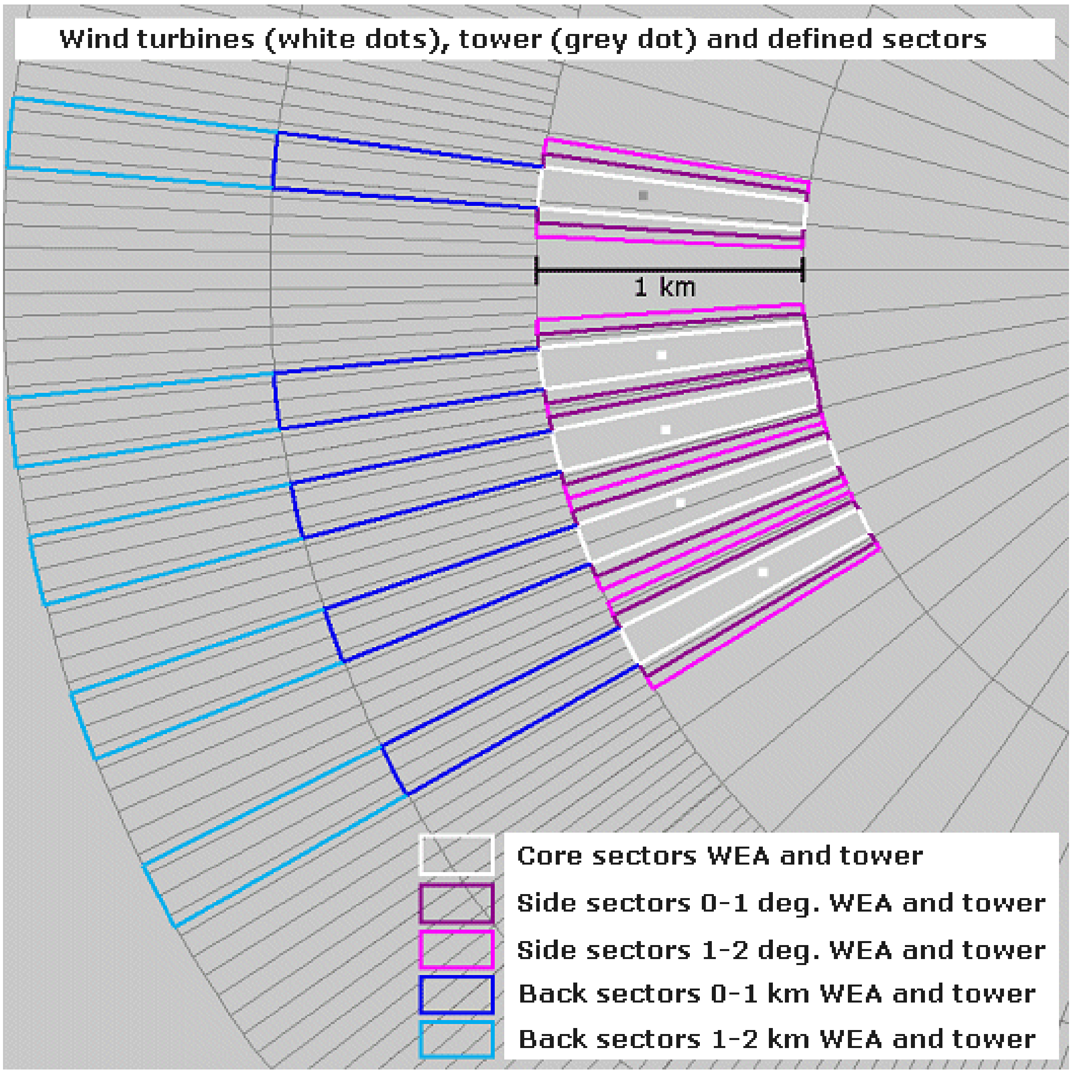

Fig. 3: The sectors defined in the vicinity of the wind turbines and the tower.

We compute the quantities DZ and DV for each radar pixel inside a sector or a group of several sectors. After processing the available time period of 12 hours, we obtain a sample of difference values that is ready for further evaluation. The number of data values representing a sector depends on the number of radar pixels within a sector but typically varies between some 100 and some 1000. Fig. 4 shows the histograms of DZ and DV for the clean sector (Fig. 4a), and for the core sectors attributed to the four wind turbines of the wind farm Aufhausen (Fig. 4b). In both figures, the PPI's at the elevation angles 0.5 and 1.5 deg. have been evaluated. In Fig. 4a we note that almost all difference values are within a threshold of 6.5 (dB or m/s, vertical lines in Fig. 4a). We take this threshold as a separator between **clean** and **affected** data values. In Fig. 4b, many data values are beyond the given threshold and can be attributed to the effects of the wind turbines (plus possibly of the ground) to the radar measurements. A significant amount of data values remain close to zero and still produce a peak in the histogram inside the interval bounded by 6.5 (dB or m/s). These data are considered as being clean, unaffected by the wind turbines, i.e. they can be used for an estimate of Z and V due to precipitation in the core sectors.

We use these properties for an estimate of the percentage amount of affected data values as a function of average radar reflectivity due to precipitation. For this, all difference values are categorized as clean or affected as described in the last paragraph. The clean values are used to calculate the average radar reflectivity (dBZ), which gives an estimate of the average precipitation intensity at a given time for a given sector. The scale of average radar reflectivity is divided into these intervals: 0-10, 10-20, 20-30, 30-40 and > 40 dBZ, and the percentage amounts of affected data on the total data sample is computed for each interval, taking into account the complete time period of 12 hours. The resulting diagrams, showing the percentage number of affected values vs. average radar reflectivity, can be considered as **footprint diagrams**, showing the degree of clutter effects (ground, buildings or wind turbines) on the radar data as a function of radar reflectivity.

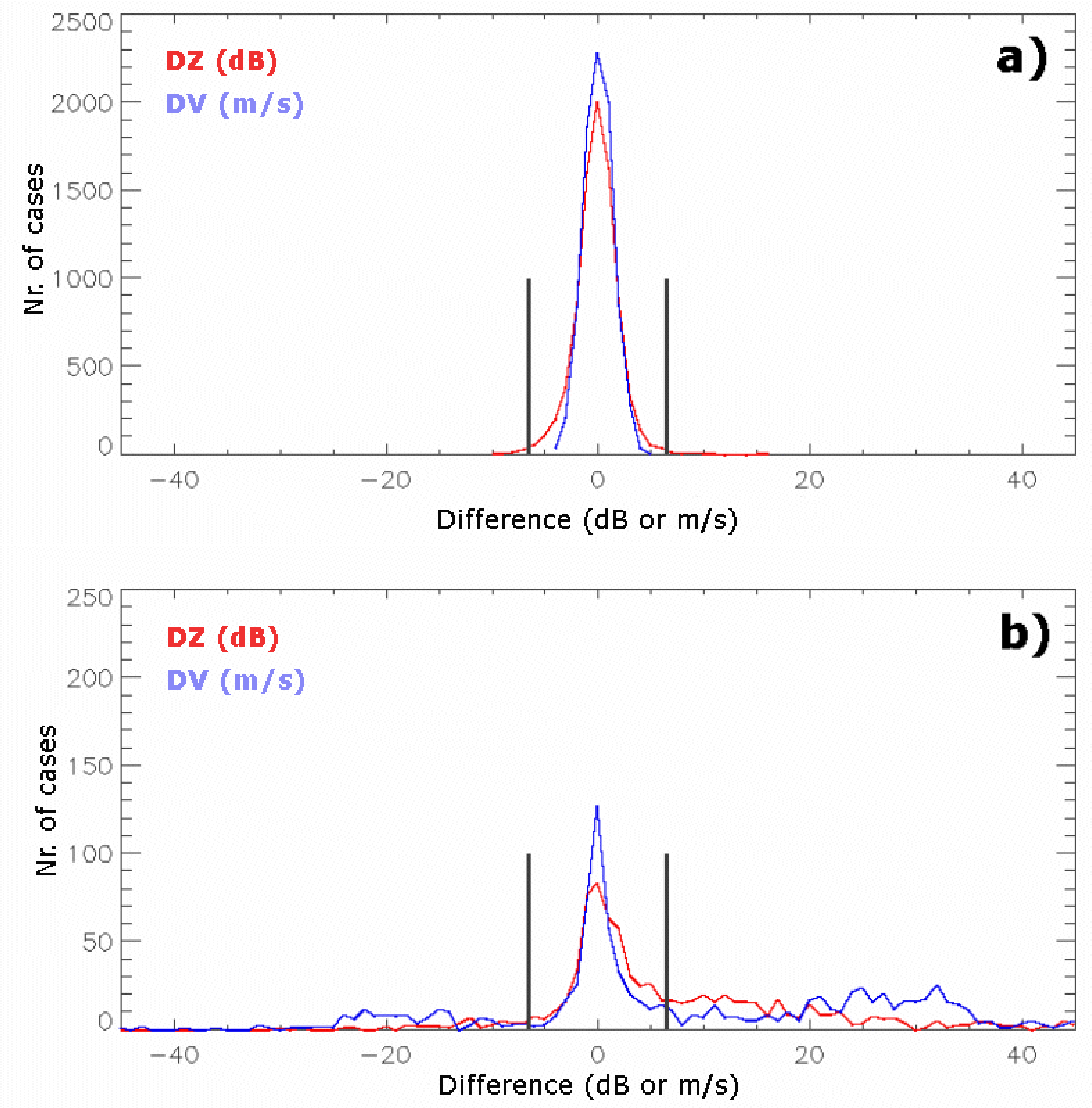

Fig. 4: Histograms of the differences DZ and DV, for a „clean“ sector (a) and the core region of the wind turbines (b) shown in Fig. 2. The vertical lines mark a threshold of 6.5 dB or m/s.

3 Results

We show and discuss a limited selection of footprint diagrams. We have to consider that the tower and additional obstacles (buildings, forests or even free fields) may affect the data in a comparable manner as the wind turbines. First, we discuss these effects with the help of Fig. 5, showing the footprint diagrams of the clean sector at the elevations 0.5/1.5 deg., and of the tower Aufhausen at the elevations 0.5/1.5 and 1.5/2.5 deg. The diagram of Fig. 5a is almost free of affected data. This corresponds to the fact that the surface below the clean sector is shadowed by hills in between the radar site and the sector. A contamination of the radar data by the ground is not possible. It is nevertheless possible that spurious effects, e.g., aircrafts or birds or random noise at low reflectivities may cause affected data values.

In contrast, the core region of the tower is heavily affected when considering the lowest possible couple of elevations (0.5/1.5 deg., see Fig. 5b). The contamination diminishes when considering the next higher couple of elevations (1.5/2.5 deg., see Fig. 5c), at least for reflectivities above 10 dBZ. This difference between the lowest possible level and the next higher level is surprising at a first glance. We explain the difference with the effects of additional obstacles on the ground, mainly trees that move with the winds and create Doppler velocities different from zero. The base height of the tower is above the height of the radar antenna. This means that not only the tower, but also trees and buildings in the neighbourhood may act as obstacles in the path of the 1 deg. wide radar beam at the elevation 0.5 deg. As a consequence, the clutter filtering based on the Doppler effect is not effective since the moving trees due to wind may produce Doppler signals different from zero m/s. At the next higher elevation, the effects of the ground are almost negligible. The tower acts as a motionless obstacle, and the clutter filter works much better than close to the ground. However, few affected data are still present up to 30 dBZ in Fig. 5c.

In order to isolate the effects of the wind turbines and to neglect the effects of other targets on the ground, it is best to consider the elevation pair 1.5/2.5 deg. At the elevation 1.5 deg., the towers and the rotor blades of the wind turbines are significant obstacles in the radar beam. The effects of these obstacles are pronounced over the whole range of reflectivity in the core sectors (Fig. 6a). In the neighboring side sectors (Fig. 6b), the percentage number of affected data diminishes above 10 dBZ, but affected data are still present up to 50 dBZ. A bit more far away from the core region (Fig. 6c) the number of affected data decreases to almost zero above 10 dBZ. We conclude that the wind turbines mainly affect a sector of five neighboring radar pixels in azimuthal direction. There may be a direct effect of the rotor blades when they are oriented perpendicular to the radar, or, there may be sidelobe effects of the radar antenna. Outside the core regions, the effects of the wind turbines are reduced to reflectivities below 10 dBZ.

The effects seen in the back sectors are given in Fig. 7. We find affected data in the reflectivity ranges up to 20 dBZ at a distance 0-2 km from the core sectors (Fig. 7 a and b). We defined additional sectors 4-7 km in the back of the core sectors. There, we find affected data up to 10 dBZ (Fig. 7c). Multi-body scattering is the probable source of the effects that are found in the sectors behind the wind turbines, seen from the radar site. The effects seem to decrease with increasing distance from the wind turbines. We did not evaluate the range 2-4 km from the core sectors, because that range is above a forested hill and may be affected by ground clutter at the elevation 1.5 deg.

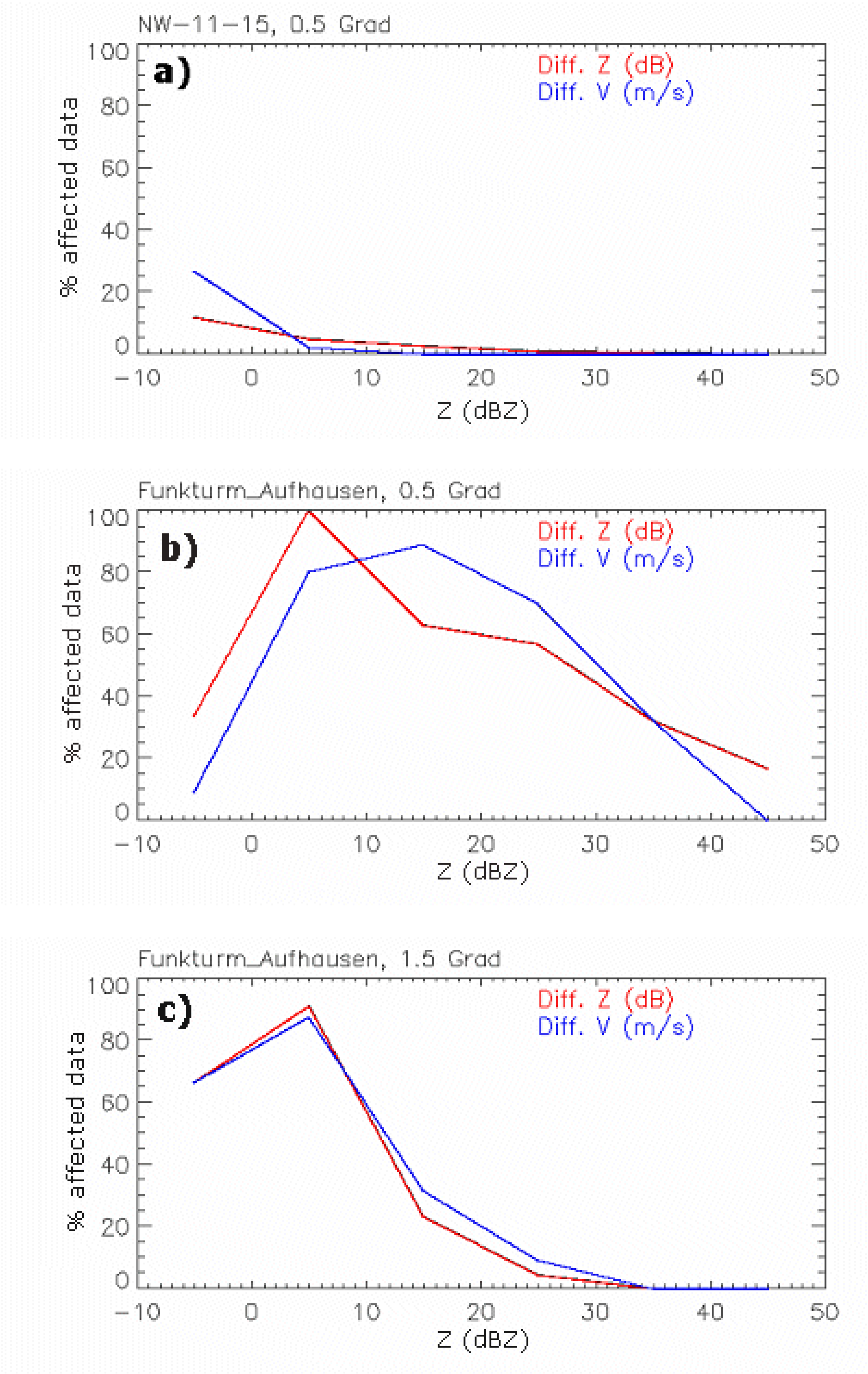

*Fig. 5: Footprin*t diagrams for a clean sector *at elevations 0.5/1.5 deg. (a), for the core sector of the tower Aufhausen at elevations 0.5/1.5 deg. (b), and for the core sector of the tower Aufhausen at elevations 1.5/2.5 deg. (c).*

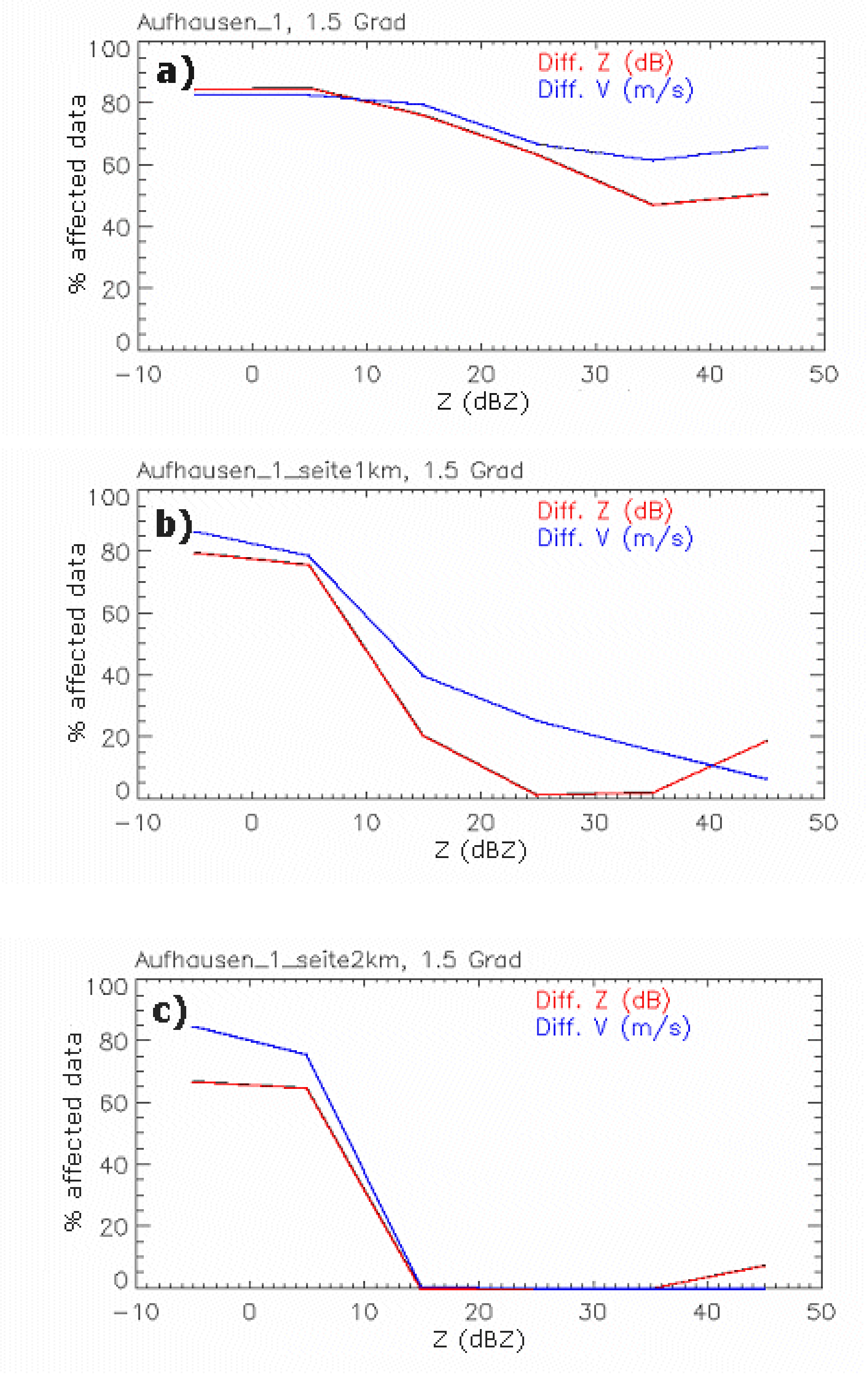

Fig. 6: Footprint diagrams of the wind farm Aufhausen at elevations 1.5/2.5 deg., for the core sectors (a), for the side sectors 0-1 km (b), and for the side sectors 1-2 km (c).

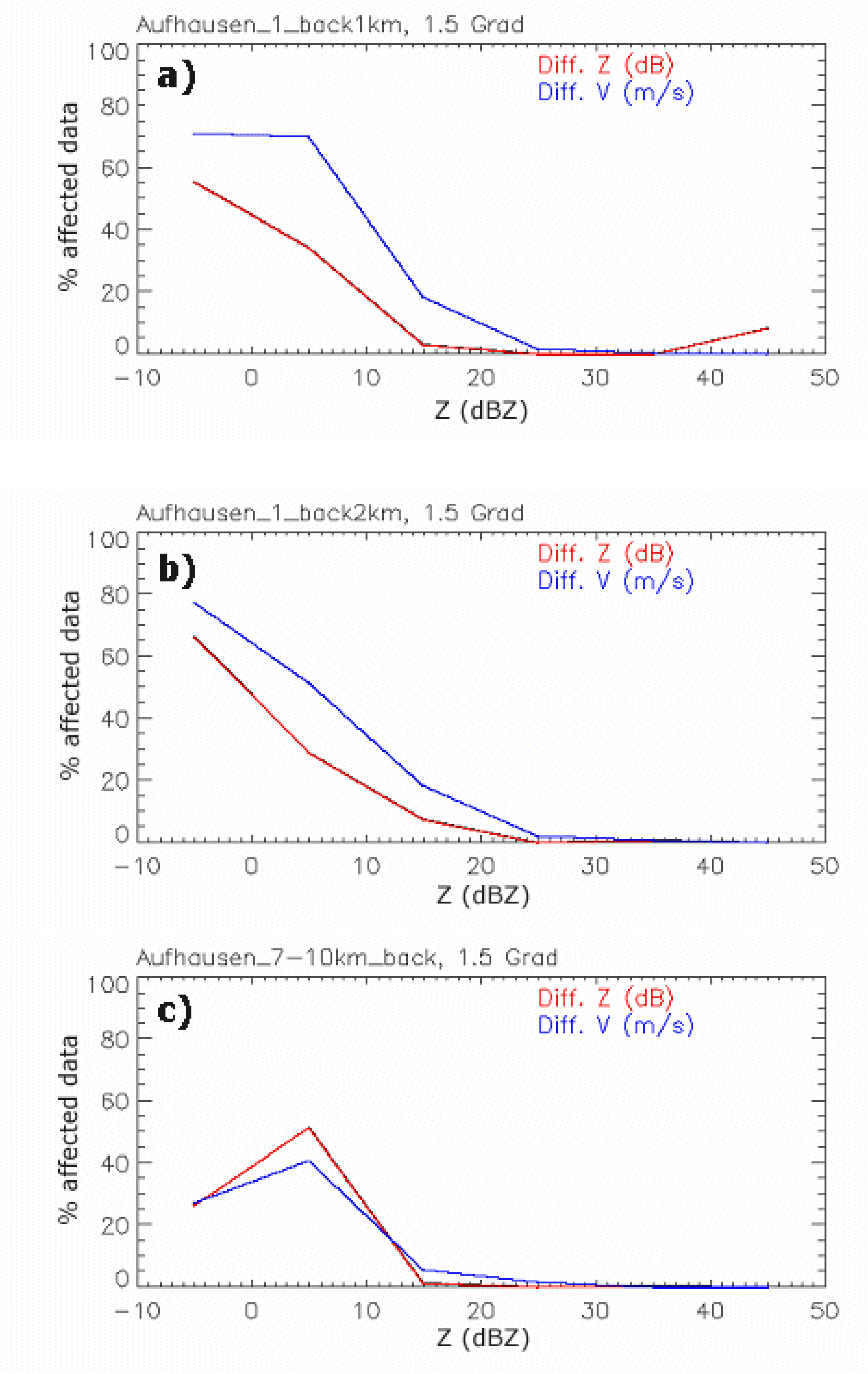

Fig. 7: Footprint diagrams of the wind farm Aufhausen at elevations 1.5/2.5 deg., for the back sectors 0-1 km (a) 1-2 km (b) and 4-7 km (c).

4 Conclusions

We propose the "big difference" method for assessment of the degree of disturbances caused by wind farms. The differences between the PPI data of two adjacent elevation angles can be used to obtain an estimate of the percentage number of data affected by the wind turbines. The effects can already be identified by means of relatively short periods of radar data. This means a big advantage compared to traditional methods that need several years of radar data for reliable statistical results. We have demonstrated the use of the big difference method with a 12-hour data sample, covering a period with clear weather, thunderstorms and stratiform precipitation on 29 May 2016.

A detailed analysis of a wind farm located at a distance of 2.5 km from the radar showed that the data up to 50 dBZ may be affected by the wind turbines in sectors around the turbines that are 5 degs wide in azimuthal direction and 1 km wide in radial direction. In the neighboring sectors, effects of the turbines are still found up to 10 dBZ on the left and right hand sides of the core sector, up to 20 dBZ on the back side within 0-2 km distance from the turbines, and up 10 dBZ in 4 to 7 km distance from the turbines. These findings are in a good agreement to the long-term studies by (Norin, 2015) and (Teschl, et al., 2016). Both studies showed that the effects outside the core sectors around wind turbines can be associated exclusively to low reflectivities, typically in the range of -30 to 10 dBZ. This is a range which is attributed either to clear-air echos (turbulence or insects) or to very weak precipitation. This range is therefore almost unimportant for operational use, e,g., for monitoring hail and heavy precipitation. A potential exception is the monitoring of weak snowfall in winter which may produce slippery conditions for traffic.

These results have been found with radar data that passed a traditional clutter filtering based on Doppler criteria. In the meantime, the German Weather Service came out with a new quality management system (called RADOLAN, (DWD 2017)) using polarisation criteria for filtering radar measurements. We are curious to analyse the effects of the wind turbines with data that passed the new RADOLAN scheme.

One should consider some requirements when the big difference method is planned for use in a specific setting. The scatter of the differences should be first tested in an environment that is not influenced by wind farms or other types of ground clutter. It should be noted that not all weather types are suitable for use of the big difference method. Fast echo motions, melting snowfall or large horizontal gradients in radar reflectivity or Doppler velocity may mask the effects of wind turbines when using the big difference method. Finally, ground clutter, especially the clutter of moving trees may also mask the effects of wind turbines.

Acknowledgement

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