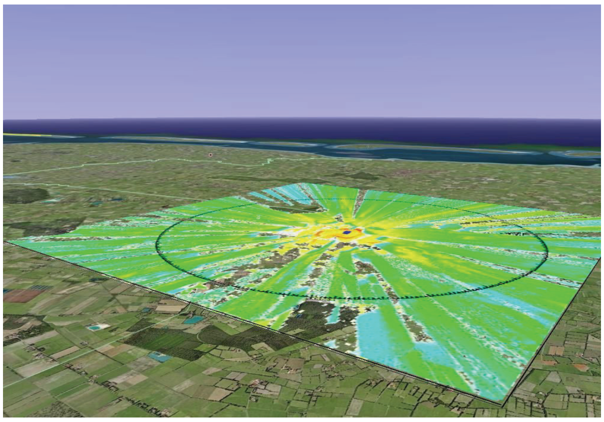
Research Project:

The Compatibility of Wind Turbines with Radars



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Full description of the project:

Improvement of the compatibility of wind turbines with radars used for air traffic control and for national defence

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1 Introduction

Since the 1990s, the use of renewable energy sources has found strong political support in Germany and other countries. To best exploit wind power, developers prefer exposed sites with plentiful wind supply, generally located in the countryside. However, since the mid 1990s, this has resulted in escalating conflicts with radar system operators.

Military and weather radars are particularly affected by these problems for the following of reasons:

1. The radar systems are located in exposed locations outside cities and residential estates
2. Military radars are very sensitive to moving objects, even at large distances
3. The interference caused by wind turbines depends on the number of turbines in a park and their spatial arrangement

The first investigations worldwide into large wind turbine arrays that took radar-related requirements from air traffic controllers into account were apparently performed in 1996 by EADS in Bremen (North Germany). To date in Germany, over 170 wind power projects – both wind parks and individual systems – have been implemented. These were investigated and optimised in order to minimise the interference that they may cause to radar systems. Resulting from the growing body of experience available to the civil and military approval authorities, the radar-related requirements for the planning of wind power plants have continuously changed since then.

1.1 Background

In recent years, the number of technical and scientific investigations in many countries has constantly increased, resulting in a significant level of accumulated knowledge being available today. For the approval of wind power plants, however, all the previous investigations, including the guidelines issued in June 2009 by EUROCONTROL, share the same disadvantage, namely that the majority of results, recommendations and guidelines are ***not*** based on systematic data recordings at military airports made during normal operation of the radars by military specialists.

1.2 Objective and results

This project was initiated with the aim of making quantitative measurements of the actual impairments to radar-based military air traffic control capability due to wind turbines in the vicinity of operational military radars, and subsequently deriving measures to reduce or avoid such impairments.

This should provide the prerequisite for an assessment basis founded on verified physical and technical criteria. This would allow the effect of wind power plants on radar systems to be evaluated and taken into account in the planning phase, thus ensuring that the approval processes are clear and transparent. In this project, the main focus was placed on primary radar positioning. Given the German Armed Forces' task to provide military air traffic control, it cannot be assumed that transponders will be used to provide secondary radar positioning.

The second objective of the research project was to investigate the effectiveness of measures on the radar systems and wind turbines for improving compatibility.

The disadvantage of not having suitable results to date that could provide a substantive legitimate basis for approving the plans for wind power plants, can thus be removed in the first step.

The results of this project show that, with currently available technology for

- optimising air traffic control radars and
- optimising the design, dimensions and spatial arrangement of wind turbines,

it is reasonably feasible to achieve compatibility between the requirements for military air traffic control and those for wind power generation.

Compared to the radar equipment currently still in use for military air traffic control in Germany, modern radars using digital signal processing offer a greater potential for compatibility since they can integrate new processes for detecting aircraft over wind power plants.

The construction techniques and materials used for modern wind turbine rotor blades provide the basis for innovative measures to reduce radar reflections. It is thus expected that changes to a wind turbine's rotor blades can result in definite improvements to its compatibility with radars, even with those in use today. This would create additional planning options for wind power plants.

The effects of these measures on compatibility have been investigated in both quantitative and qualitative terms. Subsequently, comprehensive assessment criteria have been derived from the results, which should provide the basis for approving the plans for wind turbine locations, both today and in the future.

Combining these optimisation measures for radars and wind turbines will significantly improve their compatibility.

The improvements to wind power plants will also benefit older radars still in operation, such as the ASR-910 system, and consequently result in more planning options for wind power plants.

2 Investigation of the interference to ASR-910

The effect of wind turbines on 2D air traffic control radars may be divided into two categories:

a. Display of wind turbines on the radar screen:

   A wind turbine may be displayed as a stationary target on the radar screen, with a frequency of occurrence that varies with individual settings. This applies to all currently known wind turbines irrespective of their design, dimensions or the shape of their rotor blades. All wind turbines of whatever size, located in the vicinity of a radar system, will therefore be visible on the screen. Depending on the radar resolution and the wind turbine type, each additional wind turbine may create an additional blip on the radar screen or alter the frequency of displaying an existing blip. Such blips representing wind turbines on the screen do not necessarily impair the identification and tracking of aircraft. They can, however, increase the workload on the air traffic controllers.

b. Impairment or loss of identification capability:

   During surveillance of aircraft in the direct vicinity of wind turbines, the display of primary targets is weakened when they fly over a wind park or over a dense group of wind turbines, regardless of their flight altitude. This results in restrictions to, or complete loss of the aircraft identification capability. (This loss of signal strength at all altitudes applies only to 2D radars. 3D radar systems also acquire the elevation information for determining the position of an echo signal source. This means that the restrictions in the case of 3D radars depend on the flight altitude of the aircraft concerned and are most severe when flying at low altitudes.)

In this process, the secondary radars continue to receive transponder signals from the aircraft that, for example, can no longer be identified solely by the primary radar due to the interference created by the echoes from the wind turbines. In theory, with unfavourable conditions due to the topography of the landscape or the arrangement of buildings, the strength of the signals acquired by the secondary radar can also be reduced for certain aircraft positions. This is however true even if there are no wind turbines, and is the consequence of adverse combinations in multiple-path propagation of signals due to the effects of the regional topography.

Both aspects have been systematically investigated at selected military airports. In this context, military specialists could clearly identify the locations of the wind turbines based on the above-mentioned radar displays. This allowed for a quantitative analysis to be performed on the interference caused to aircraft identification. The methods used and the results of this analysis are presented in this report.

The precision of locating targets with radar is defined by the technical resolution, which depends on distance and azimuth angle. Using the ASR-910 system, the distance can be determined with a precision of 300 m and the bearing with a precision of 3.1°. This resolution zone will be referred to as the “interference cell” in this report. A spatial separation between two objects, i.e. in this case the discrimination between a wind turbine and an aircraft, is only possible if the difference in position exceeds these values.

The resolution zone of future radars will differ in size depending on the individual radar concept. With the ASR-S, the ASR-910 system’s radial resolution will be not improved.

The ASR-ES, derived from the ASR-S by HW and SW modifications as a system that has been designed to minimize the impact of wind turbines, the aim is to achieve a radial sigificant reduction also of the interference cell diameter in range. This is done – without changing the nominal range resolution – using special signal processing techniques. This means that the separation of objects based on the distance will be clearly improved. However, the additional improvements resulting from the optimised data and signal processing of digital radars have not yet been taken into account here.

2.1 Restrictions to aircraft / primary target identification

The display of wind turbines on air traffic control radars at selected locations was observed and documented, taking the parameters listed below into account. The airports concerned were selected in accordance with recommendations made by the German Armed Forces’ Office for Air Traffic Control (AFSBw), which was based on operational criteria, i.e. the high number of wind turbines (Wittmund, Nordholz and Holzdorf) and the availability of radar systems, including the advanced ASR-S (Büchel).

The observations and recordings were made

- by a variety of different individuals (professional air traffic controllers),
- over a relatively long period of time,
- on a variety of different types of wind turbines (with regard to rotor diameter and rotor speed),
- on wind turbines oriented in a variety of different directions,
- for a variety of different wind directions,
- for a variety of different rotor orientations and
- for a variety of different terrains.

2.1.1 Survey of wind turbines

The following table provides an overview of the distances and bearings of the wind park locations selected for the collection of data. They were accessible for continuous observation by the controllers and were also in operation while the data was being collected, i.e. the rotors were in motion.

Location	Group	Direction	Distance
Nordholz: **N-1**	**Test field**	**approx. 35°**	**approx. 11 km**
N-2	**Nordleda**	**approx. 78°**	**approx. 10 km**
N-3	**Midlum**	**approx. 180°**	**approx. 2.7 km**
N-4	**Spieka**	**approx. 290°**	**approx. 5.7 km**
Wittmund: **W-1**	**Utarp-Holtriem**	**approx. 290°**	**approx. 16.9 km**
W-2	**Königsmoor**	**approx. 218°**	**approx. 6.3 km**
W-3	**Eggelingen**	**approx. 66°**	**approx. 16.6 km**
Holzdorf: **H-1**	**near Hohenseefeld**	**approx. 41°**	**approx. 16.3 km**
H-2	**near Herzberg**	**approx. 132°**	**approx. 8.7 km**
H-3	**near Listerfehrda**	**approx. 288°**	**approx. 19.7 km**
Büchel: **B-1**	**near Lirstal**	**approx. 350°**	**approx. 8.4 km**
B-2	**in front of Lirstal**	**approx. 350°**	**approx. 7.3 km**
B-3	**behind Eulgem**	**approx. 50°**	**approx. 12.5 km**
B-4	**near Reidenhausen**	**approx. 125°**	**approx. 24.6 km**

Table 1: Wind park within the range of detection while collecting the data

With regard to the frequency of displaying the wind turbines, the data recorded at the individual airfields were grouped in the following categories:

a. The wind turbines were continuously visible on the screen, i.e. at almost every rotation of the aerial.

In this case, it is not possible for a controller to reliably detect and identify a primary target / aircraft flying over a group of wind turbines.

b. The wind turbines were frequently visible on the screen, however, not at every rotation of the aerial.

In this case, there is a significant impairment to a controller’s ability to reliably detect and identify a primary target / aircraft flying over a group of wind turbines.

c. The wind turbines were rarely visible on the screen, and not in direct sequence.

In this case, it is possible for a controller to reliably detect and identify a primary target / aircraft flying over a group of wind turbines.

For air traffic control using the **ASR-910** system, whose impairments due to wind turbines were the focus of these measurements, the following general principle applies:

- Additional information from transponders can only be used if manually requested by the controllers for individual objects. However, in contrast to the usual form of display on the ASR-S, it is not possible to show all the information from the transponder signals on the screen (refer to the notes on the support of transponders according to section 1.2). Therefore, the usable transponder information was not taken into consideration for assessing the interference as described below.

To aid in evaluating the results visually, the assessments have been colour coded as follows in the tables and diagrams:

- Red = category a
- Yellow = category b
- Green = category c

As an example, the data collected for Nordholz airport is shown here:

				Standort 1	Standort 2	Standort 3	Standort 4
	Nordholz			Nr. 1: E 112	Nr. 1-3: E 40	Nr. 63-70: E 40	Nr. 8-10: V 44
				NH: 116 m	NH: 48 m	NH: 32 m	NH: 52 m
Beobachtete WEA				Testfeld	Nordleda	Midlum	Spieka
Kennzeichnung gemäß Karte:				aus Gruppe A	aus Gruppe B	aus Gruppe F	aus Gruppe G
Datum: *dd.mm.jj*	***Zeitraum:*** *hh:mm bis hh:mm*	***Windrichtung ° /***	***Windstärke kn***	RQS: 27 dBsm	RQS: 18 dBsm	RQS: 18 dBsm	RQS: 19 dBsm
11.02.2008	13:00 - 13:30	45	6	o	/	x	/
13.02.2008	10:00 - 10:30	45	6	o	x	x	/
13.02.2008	14:30 - 15:30	45	8	o	/	x	/
15.02.2008	11:30 - 11:40	60	14	o	x	x	x
27.03.2008	18:45 - 19:00	70	6	o	x	x	/
11.02.2008	08:30 - 09:00	90	10	o	x	x	/
20.02.2008	09:30 - 10:00	130	6	o	/	/	o
28.03.2008	08:45 - 09:00	160	8	/	x	x	/
20.02.2008	13:45 - 14:15	180	8	o	o	/	o
10.03.2008	10:00 - 12:00	180	15-22	/	x	x	/
11.03.2008	09:00 - 10:00	210	10-15	x	x	/	/
25.02.2008	17:50 - 18:30	220	7	/	x	x	x
26.02.2008	10:00 - 11:00	220	8	o	x	x	/
07.03.2008	10:15 - 10:45	220	10-12	/	/	x	o
12.02.2008	14:45 - 15:15	225	5	o	x	/	/
28.02.2008	09:00 - 10:00	230	10	o	x	x	/
11.03.2008	16:00 - 16:30	230	12-20	x	x	x	/
29.02.2008	10:00 - 11:00	240	8	o	x	x	x
21.02.2008	08:00 - 08:30	240	10	o	x	x	o
28.03.2008	11:30 - 11:45	240	12	/	x	x	/
22.02.2008	12:00 - 13:00	240	18-22	/	x	x	/
25.02.2008	14:00 - 14:30	250	14	/	x	x	x
06.03.2008	08:12 - 08:42	250	17	/	x	x	/
22.02.2008	10:00 - 10:30	250	15-25	o	x	x	/
26.02.2008	17:00 - 17:30	260	20	/	x	x	o
27.02.2008	15:00 - 15:30	260	25	/	x	x	/
25.02.2008	10:00 - 11:00	260	10-14	/	x	x	x
19.03.2008	13:30 - 14:00	260	12	/	x	x	/
06.03.2008	15:00 - 15:30	260	15-23	x	x	x	o
14.02.2008	10:00 - 10:30	270	5	o	/	x	o
12.02.2008	09:10 - 09:40	270	6	o	/	x	o
28.02.2008	15:00 - 15:30	270	12	x	x	x	/
19.02.2008	08:30 - 09:00	270	18	o	/	x	/
13.03.2008	13:10 - 13:40	270	25	o	x	x	/
04.03.2008	08:45 - 09:00	300	25	o	x	x	x
04.03.2008	11:15 - 11:35	310	6	o	/	x	x
14.02.2008	15:00 - 16:00	315	6	o	x	x	/
15.02.2008	10:00 - 11:00	315	10	o	x	x	/
18.03.2008	16:15 - 16:35	330	15	o	/	x	/
18.03.2008	10:30 - 10:45	330	20	o	/	x	/
04.03.2008	09:00 - 09:30	350	18	o	x	x	x
	Durchschnittswerte		**11,3**	**48% großer Rotor**	**83%**	**87%**	**64%**

X : WEA - Störung durchlaufend feststellbar/sichtbar ~ Häufigkeit größer 90%

/ : WEA - Störung kurzzeitig, aber oft feststellbar/sichbar ~ Häufigkeit größer 66%

0 : WEA - Störung nicht oder nur selten kurzzeitig feststellbar/sichtbar~ Häufigkeit kleiner 33%

Table 2: Record of the frequency of appearance of wind turbines in Nordholz

Frequency of interference results at Nordholz

The records show that there is a clear effect on the radar screen resulting from the diameter of the rotors and their speed. Larger rotors cause less frequent interference since they rotate more slowly. In this context, it was not possible to establish any significant differences between the various brands of wind turbines. For wind turbines with very large rotors that are located close to a radar system, it cannot be excluded that the radar will detect a periodic tangential movement over very short paths (e.g. at the location N-1).

Based on the observations recorded at Nordholz, the following values can be specified as an average for the entire period of observation, of the frequency of interference on the radar screen from the individual wind turbines involved.

For location N-1:
48 % for wind turbines with a rotor diameter in excess of 110 m
An additional technical aspect was not considered here, which results from the above-mentioned sideways motion of large rotors due to the large lateral dimensions in relation to the distance to the radar location.

For location N-2:
83 % for wind turbines with a rotor diameter of 40 m

For location N-3:
87 % for wind turbines with a rotor diameter of 40 m

For location N-4:
64 % for wind turbines with a rotor diameter of 44 m

Frequency of interference results at Wittmund

The observations here show a varying frequency of appearance on the screen for similar wind turbines. In this context, it must be noted that a beneficial influence from shadowing effects could not be excluded at location W-1 (at a bearing of 290°). At location W-3 (at a bearing of 66°) there is a group of at least 16 wind turbines of the same type with rotor diameters measuring between 66 and 70 m, together with three smaller systems with approx. 40 m large rotors. The photographic and video records show that they are always displayed at a maximum of 13 to 14 times, corresponding to a frequency of appearance of approx. 72 % (refer to fig. 1).

Based on the observations recorded at Wittmund, the following values can be specified as an average for the entire period of observation, of the frequency of appearance on the radar screen of the individual wind turbines involved.

For location W-1:
33 % for wind turbines with a rotor diameter of 66 m
In this context, no account was taken of an additional beneficial aspect resulting from the lower part of the rotor being shaded by the local topography.

For location W-2:
72 % for wind turbines with a rotor diameter of 66 m

For location W-3:
72 % for wind turbines with a rotor diameter of 70 m

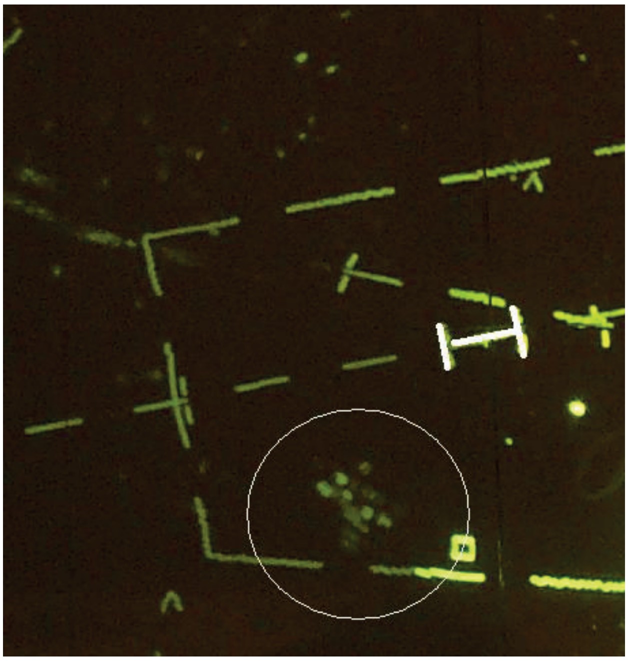


Fig. 1: Details of the radar display in Wittmund

The wind park, consisting of 16 wind turbines of the same type with rotor diameters of approx. 66 m and 3 systems with approx. 40 m large rotors, is marked on the picture. The varying intensity of displaying the turbines due to the individual speed of rotation of their rotors is clearly visible. Wittmund airport is highlighted in white.

Frequency of interference results at Büchel (ASR-910)

The observations here show a similar frequency of appearance for all wind turbines. The wide variety of distances has no effect on the frequency of appearance. All wind turbines have similar diameter rotors. The different alignment of the locations results in different rotor orientations.

Based on the observations recorded at Büchel, the following values can be specified as an average for the entire period of observation, of the frequency of appearance of the individual wind turbines on the radar screen.

For location B-1:
72 % for wind turbines with a rotor diameter of 70 m

For location B-2:
72 % for wind turbines with a rotor diameter of 66 m

For location B-3:
74 % for wind turbines with a rotor diameter of 70 m

For location B-4:
69 % for wind turbines with a rotor diameter of 70 m

Frequency of interference results at Büchel (ASR-S)

The selected wind turbines as described above as well as others within the range of detection of the ASR-S create so-called “plots” that are not displayed on the radar screen during normal operation, in contrast to the ASR-910.

With regard to the “tracks” that are displayed in their location during normal operation, ***no*** unwanted appearance of wind turbines was observed. This corresponds to the investigations into the effectiveness of ASR-S signal and data processing, relating to the suppression of objects on the ground (refer to section 3).

Frequency of interference results at Holzdorf

The observations here indicate a varying frequency of appearance of the wind turbines on the screen. For some observation periods, only single channel operation was possible. However, no difference could be determined with respect to two channel operation.

The rotor diameters were approx. 76 m at locations H-1 and H-2 and approx. 80 m at H-3.

The results for location H-3 (at a bearing of 50°) illustrate the impact of dense wind parks at great distances. The distinct differences in the recorded frequency of appearance are due to the resolution of the existing radar not being capable of separately displaying adjacent wind turbines. (This also applies to new air traffic control radars such as the ASR-S whose resolution is only slightly different from the existing ASR-910.) At the same time, this shows the problem of superimposing several wind turbines on the display. In this case, the effects of two wind turbines of the same type with rotor diameters of approx. 80 m merge, resulting in a combined interference frequency of around 76 %, although each individual system only appears at a frequency of approx. 53 %.

It is important in this context to note that most of the wind turbines at location H-3 are of the same type as the systems considered previously, i.e. at Wittmund, Nordholz and Büchel. The relevant differences result solely from the longer rotor blades, while there are no changes to the profile of the blades, the shape of their surfaces or the lightning conductor system. It must also be noted that rotor blades of this type of wind turbine rotate at a lower speed.

Based on the observations recorded at Holzdorf, the following values can be specified as an average for the entire period of observation, of the frequency of appearance on the radar screen of the individual wind turbines involved.

For location H-1:
67 % for wind turbines with a rotor diameter of 76 m

For location H-2:
47 % for wind turbines with a rotor diameter of 77 m

For location H-3:
76 % for two overlapping wind turbines with a rotor diameter of 82 m

2.1.2 Assessment of the survey

The following diagrams show the results of this analysis in a standardised form with the aid of examples. The results were standardised with respect to the bearing from the radar location, the wind directions as well as the rotor axis, and arranged in groups according to the rotor diameter and the rotor speed.

In each case, the picture on the left shows a polar diagram of the observations in the assessment (using the colours red, yellow and green), which are arranged according to the frequency of appearance as noted by the air traffic controllers: “continuously”, “frequently” or “rarely”. The records made of the appearance of the wind turbines on the radar screen were supplemented with details about the weather and wind, which aided in determining the orientation of the rotors in relation to the radar, both for azimuth and wind strength (line length).

The diagram on the right shows the categories of average interference, colour coded "red", "yellow" and "green" corresponding to "strong", "medium" and "weak", respectively "continuously", "frequently" and "rarely", based on the orientation of the rotor axis to the location of the radar.

The wind turbines shown for comparison have been categorised according to rotor diameters from 40 to 44 m (essentially corresponding to older units), from 66 to 76 m, from 82 to 100 m, and finally exceeding 100 m. The latter corresponds to the new type of large wind turbines that are specifically intended for the planned offshore plants.

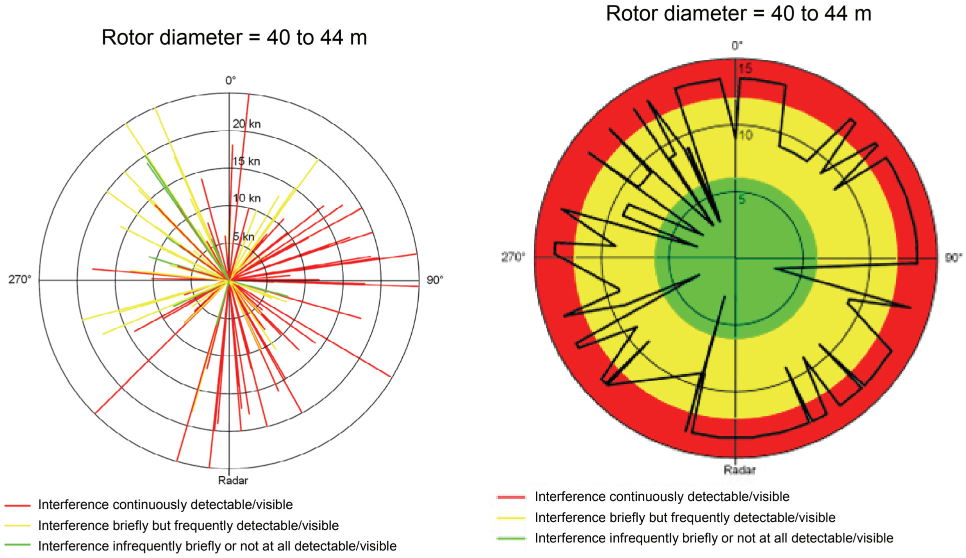


Fig. 2: Frequency of appearance of wind turbines with a rotor diameter from 40 to 44 m

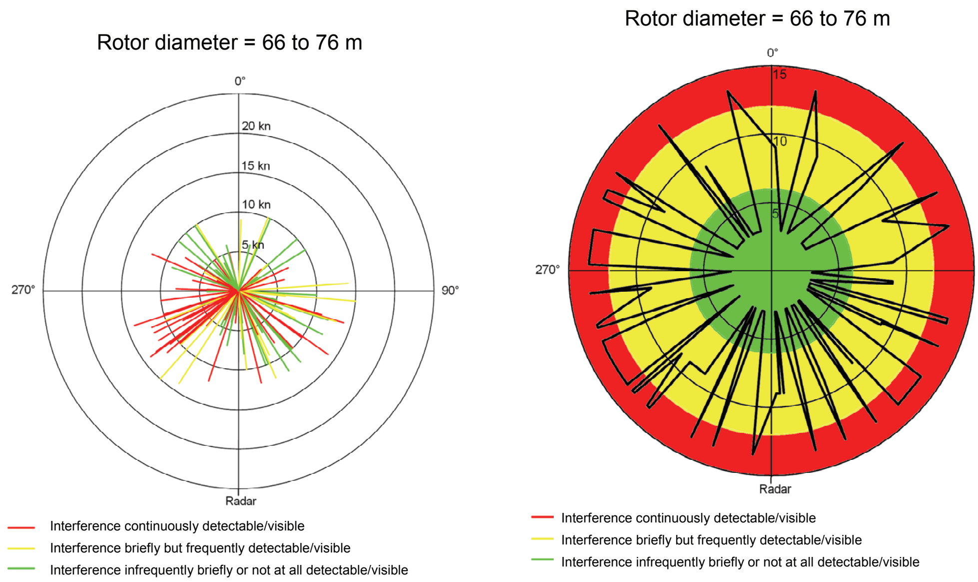


Fig. 3: Frequency of appearance of wind turbines with a rotor diameter from 66 to 76 m

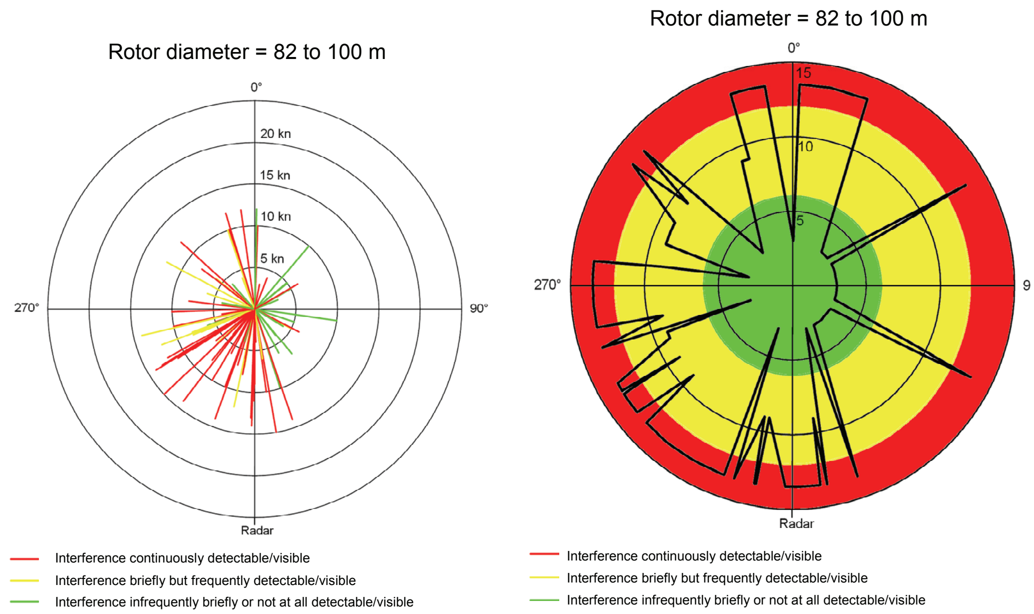


Fig. 4: Frequency of appearance of wind turbines with a rotor diameter from 82 to 100 m

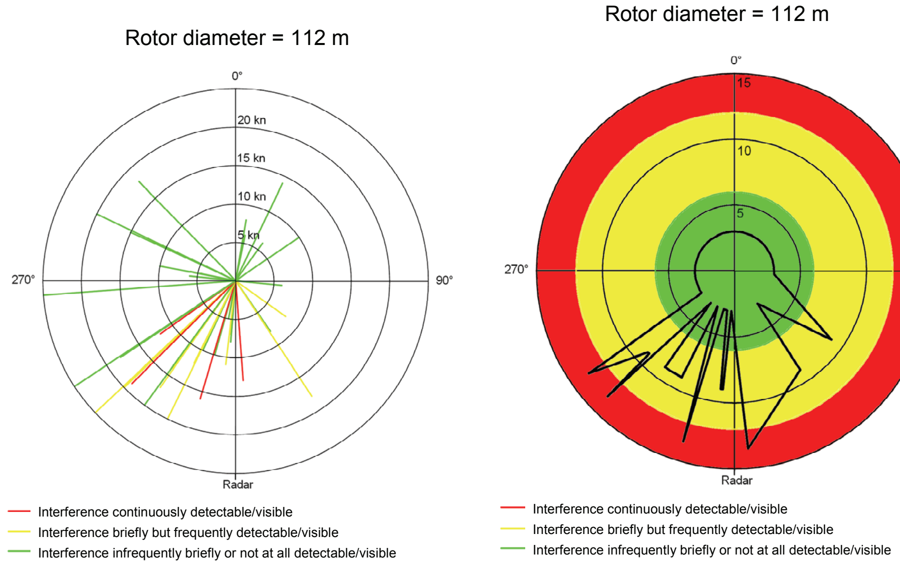


Fig. 5: Frequency of appearance of wind turbines with a rotor diameter in excess of 100 m

2.1.3 Assessment of the results

Arranged in order of rotor diameter, the main characteristics may be summarised as follows:

- Wind turbines with a rotor diameter from 40 to 44 m:

  Appear very frequently on the radar screen, irrespective of the rotor orientation, and are therefore displayed to the controller at almost every rotation of the aerial.

- Wind turbines with a rotor diameter from 66 to 76 m:

  Appear most frequently with a rotor orientation between 20° and 60°. Appearance is less frequent for a viewing angle of approx. 0° (i.e. the rotor axis points in the direction of the radar).

- Wind turbines with a rotor diameter from 82 to 100 m:

  Appear infrequently, irrespective of the rotor orientation. Where they do appear, it is mainly with a rotor orientation between 20° and 70°. Depending on the design, distinct differences could be observed with regard to the frequency of appearance.

  Appearance is less frequent for a viewing angle of approx. 0° (i.e. the rotor axis points in the direction of the radar).

- Wind turbines with a rotor diameter in excess of 100 m:

  Appear infrequently for all directions. Significant clusters appeared for low radial speeds e.g. for an observation angle of approx. 90° (viewing angle orthogonal to the rotor axis).

It can thus be seen that as the diameter of wind turbine rotors increases, the frequency of appearance on the radar screen decreases, although the absolute radar cross section (RCS) in general increases with increasing rotor diameter.

The frequency of appearance does not depend on the density of the systems, or on the distance from the radar site. If wind turbines are placed very close together, two or more systems may overlap, which can negate the advantage of slower rotor speeds. The orientation of the rotors to the radar has little influence. However, the frequency of interference is clearly reduced for an angle of 0° between the rotor axis and the direction to the radar site, and increases to the specified values for orientation angles of between 60° and 90°.

In addition to its speed, the frequency of appearance of a wind turbine on a radar screen depends strongly on the strength of the reflection and on the shape of the rotor blades. However, it will only be possible to make a more general statement about a reduced frequency of appearance after performing a comparative analysis of the shape and material of rotor blades.

One explanation is provided by the design principle that rotor speed decreases when rotor diameter increases.

Rotor diameter	Typical rotor speeds
40 - 44 m	12 - 34 rpm
60 - 76 m	9 - 21 rpm
80 - 100 m	9 - 19 rpm
> 100 m	8 - 13 rpm

Table 3: Typical rotor speeds for different sizes of wind turbines

Lowering the rotor speed decreases the probability to observe a rotor blade position that allows total reflection at the time of radar illumination due to the orientation of the aerial. To ensure an exact interpretation of these results, the wind turbine structures were simulated as 3D CAD objects in accordance with the recorded data and then analysed with respect to their reflection characteristics.

As a general principle, these results also apply to the frequency of appearance of “plots” in the signal and data processing chain of the ASR-S radar. As already mentioned above, the wind turbines observed at Büchel did ***not*** produce any interfering bursts of appearances on the screen of this advanced radar that has digital signal and data processing capability and comparatively high Doppler resolution. This can be explained by the measures already taken there to suppress the display of objects on the ground. However, in the environment of the Büchel ASR-S location, the wind turbines are not arranged in large groups. It is therefore not viable to transfer these results to the radar’s potential behaviour in extended wind parks.

2.2 Analysis of reflections from wind turbines

The 3D CAD models of typical wind turbines and their rotor blades take the following conditions into account:

- Rotor orientation in relation to the reference direction to the radar site
- Orientation of the rotor blades
- Rotor diameter
- Rotor speed
- Rotor shape

The analysis of the RCS in the frequency range of the radar systems considered, which was based on the characteristics and far field conditions of the aerial, provided the results discussed in the following paragraphs.

Figures Fig. 6 to Fig. 8 illustrate the typical reflection patterns from a wind turbine for one complete 360° rotation of a rotor based on the various rotor orientations and the radar site. In this context, the individual rotor speeds must be noted when referring to the illustrations. The average rotation period for a system with a 70 m rotor can be specified as 13.5 seconds.

In each case, 6 distinctive peaks can be seen. They are produced by orthogonal illumination of the leading and trailing edges of each blade when the 3 rotor blades are vertically orientated. These 6 reflection peaks therefore occur at periodic intervals of approx. 13.5 seconds.

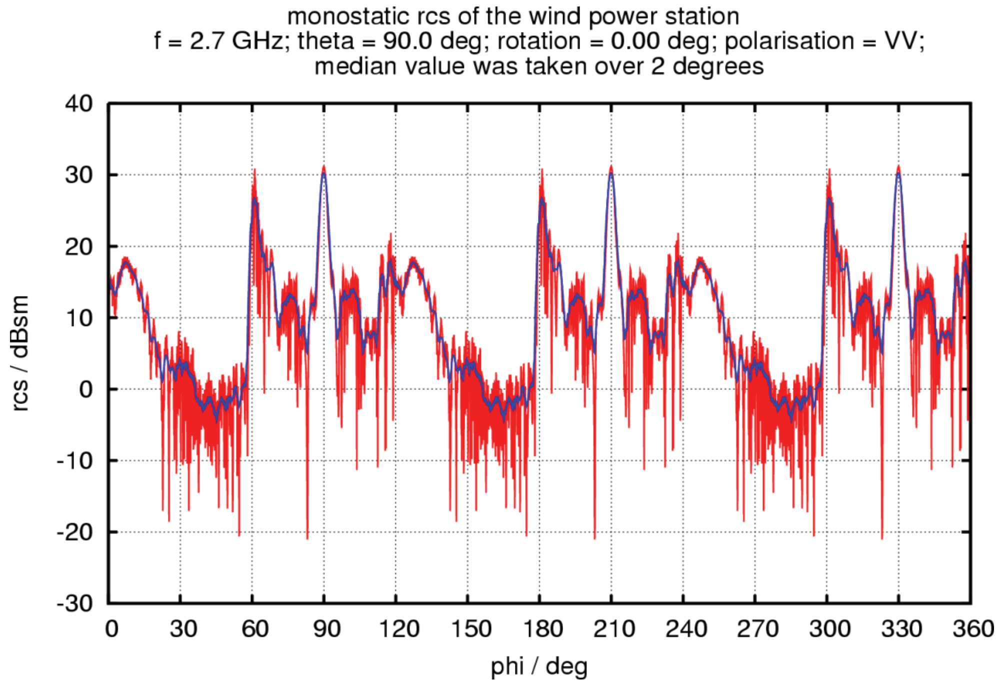


Fig. 6: RCS versus rotor position, rotor orientation of 90°, wind turbine with 70 m rotor

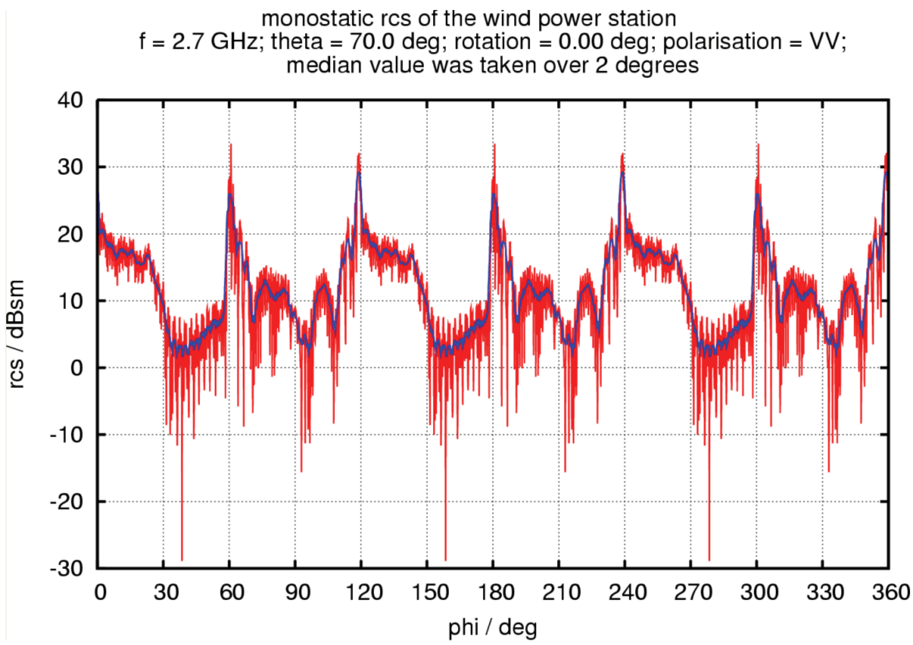


Fig. 7: RCS versus rotor position, rotor orientation of 70°, wind turbine with 70 m rotor

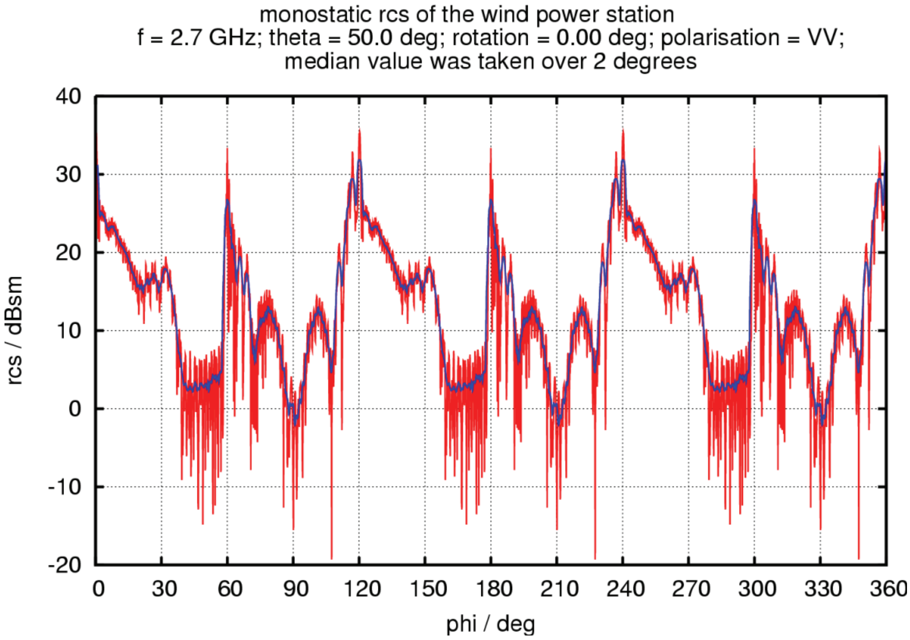
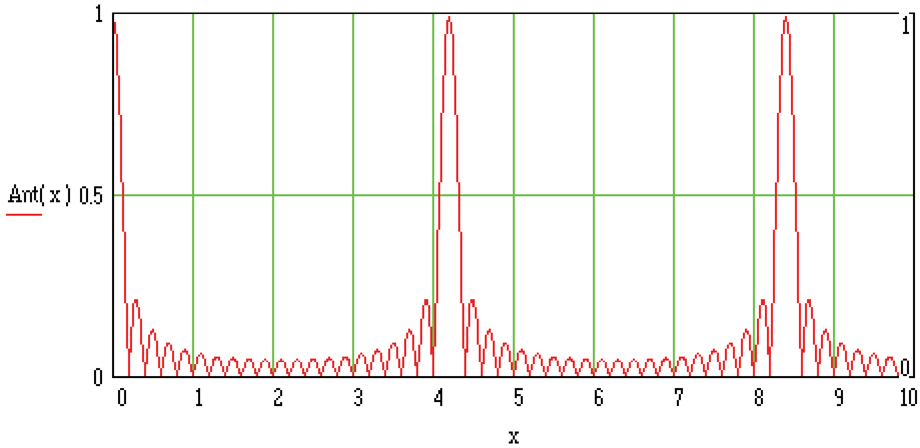


Fig. 8: RCS versus rotor position, rotor orientation of 50°, wind turbine with 70 m rotor

A 120° periodically-repetitive pattern can be observed that corresponds to the symmetrical construction of the 3 blades.

The main reflection-relevant observations for vertical orientation of one of the rotor blades illustrate that, as wind turbines get larger and consequently the rotor speeds get slower, the Doppler shift in the radar echo signal become less, resulting in a lower frequency of strong interference from reflections compared to smaller, faster rotating wind turbines. At the same time, taking account of the rotational speed of the radar aerial, the number of possible detections is reduced.

The frequency of appearance (or interference) of a wind turbine is determined by how often the rotating radar aerial is aligned with it, as well as by how often it reflects the radar signal with a sufficiently strong Doppler component for a sufficiently long period of time. The following figure shows the sensitivity of the ASR-910 radar over time, in the direction of a particular wind turbine.



Antenna orientation in the direction of wind turbines x/sec

Fig. 9: Periodicity of the ASR-910 radar aerial

If one considers the partial surface treatment of a rotor blade to reduce radar reflections, treatment of the inner ¼ of the blade at its root provides a clear advantage over treatment of the outer ¼ of the blade at its tip.

This indicates that measures on the rotor blade are obviously more efficient if implemented in the proximity of the blade root. Most of the reflections are coming from this area due to the low surface curvature of the inner part of the blade.

This result contradicts the assertion frequently heard that interference of wind turbines with radars is mainly due to the high speed of the blade tips.

Based on this finding it will be possible to effectively reduce the frequency of appearance of wind turbines on radar screens with both current radars such as the ASR-910 as well as with the future ASR-S system. This principle can be applied to all primary radars.

The exact mechanisms to reduce radar reflections from rotor blades do however strongly depend on the design and shape of the individual blades, which vary from manufacturer to manufacturer. For this reason, no generalisation is possible.

2.2.1 Analysis of the dynamic RCS of wind turbines

Amongst the options presented by the signal and data processing in advanced radars, the Doppler characteristics of the reflections from wind turbine rotors are of particular importance.

Fig. 10 shows the basic division of the received Doppler spectrum for radars with moving target detection capability (ASR-910, ASR-S, but also air defence radars).

The area shaded in blue ($P < P_{threshold}$ and/or $|f| < \Delta f_0/2$) marks the area of the received signal spectrum to which the radar is insensitive. Signals appearing only in this area will not result in a target being displayed on the radar screen.

However, signals appearing in the yellow-shaded area will result in a target being displayed.

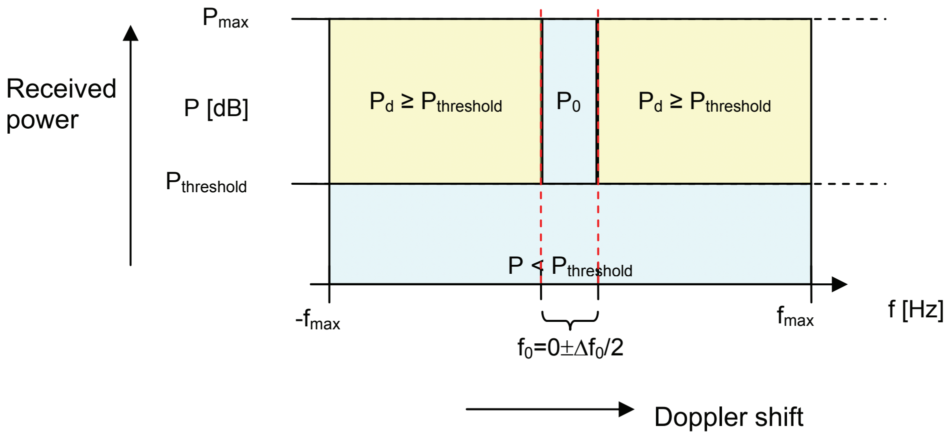


Fig. 10: Division of the Doppler spectrum into areas relevant for setting off alarms

The thresholds shown for the Doppler shift and the reception level basically depend on the radar under consideration.

In general, the Doppler spectrum is not unambiguously captured by the radar. For this reason, Doppler shifted signals above f_{max} or below $-f_{max}$ will also be shown in the area between $-f_{max}$ and f_{max}.

This information can be processed by multi-stage Doppler filters to use the spectral distribution of the echo signal as a signature to identify a wind turbine. In addition to the width of the Doppler spectrum, the signal strength over frequency is also of significance here.

In the diagrams below, examples of the Doppler spectra are shown for rotors with a diameter of 40 and 80 m, different operating speeds and with rotor orientations of 70° and 90°.

This was always based on the minimum and maximum typical rotor operating speeds as specified by the manufacturer.

For all results (refer to fig. Fig. 11 to Fig. 14), “snapshots” were taken in each case for three different rotor positions. The following applies here:

0° => Leading edge of the rotor blade is vertical

30° => Tip of one blade is pointing to the radar site

60° => Trailing edge of the rotor blade is vertical

The significance of the “Doppler frequency” axis is the same as described for Fig. 10. In contrast to that however, the entire Doppler frequency range is shown here, regardless of the range of unambiguous frequencies that can be measured by the radar unit concerned.

Example results for the 40 m rotor without presuming measures to reduce radar reflections

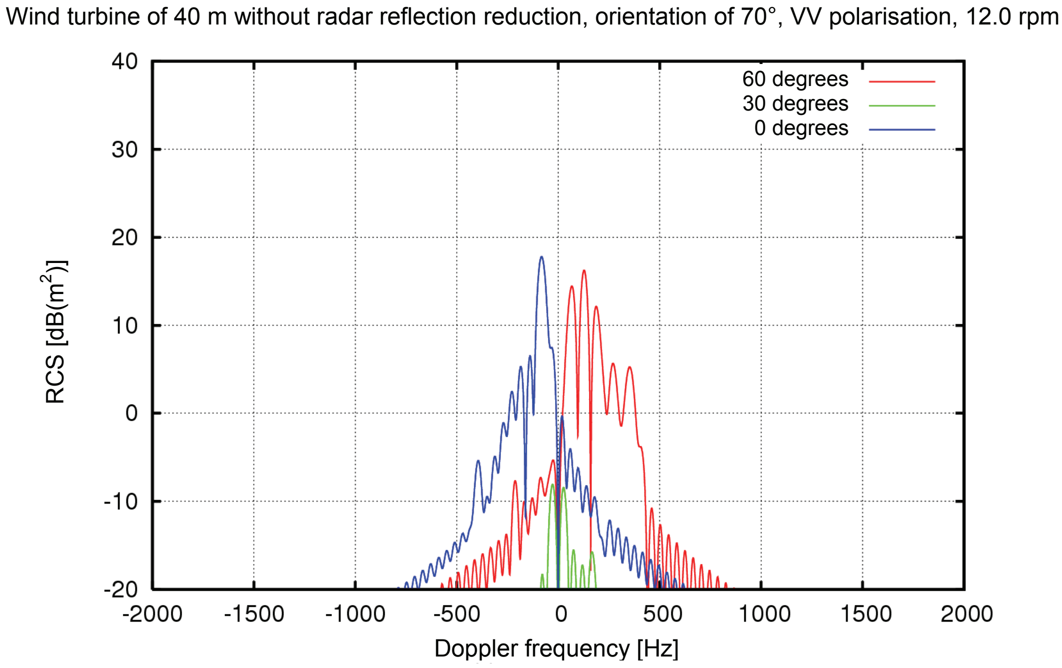


Fig. 11: Doppler spectrum at low speed of 12 rpm, rotor orientation of 70°

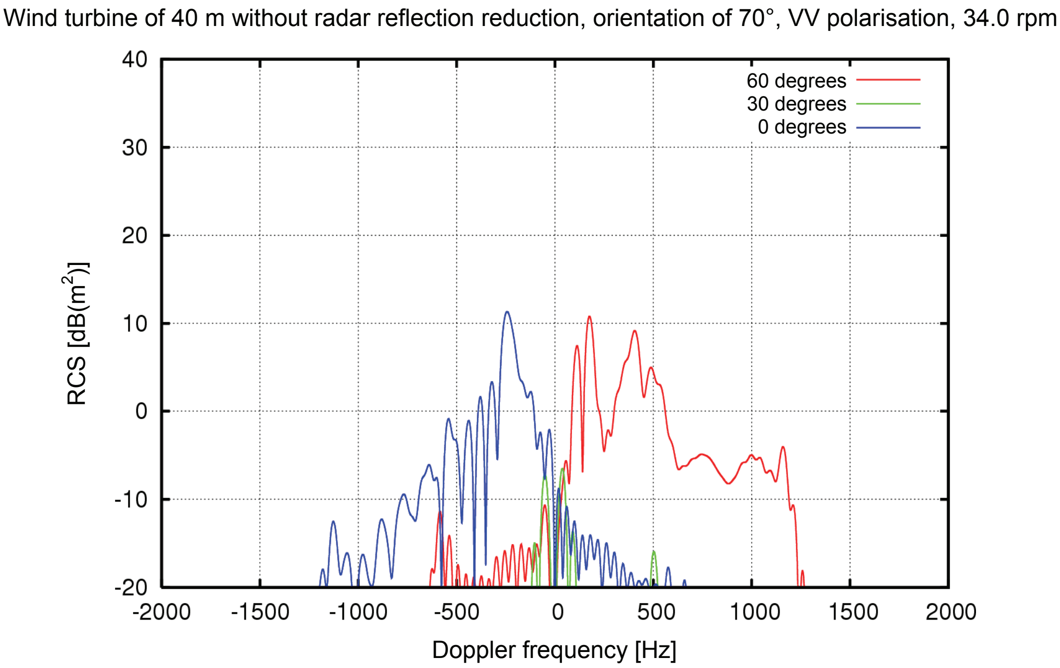


Fig. 12: Doppler spectrum at high speed of 34 rpm, rotor orientation of 70°

Example results for the 82 m rotor with and without presuming measures to reduce radar reflections

Wind turbine of 82 m without radar reflection reduction, orientation of 90°, VV polarisation, 19.5 rpm

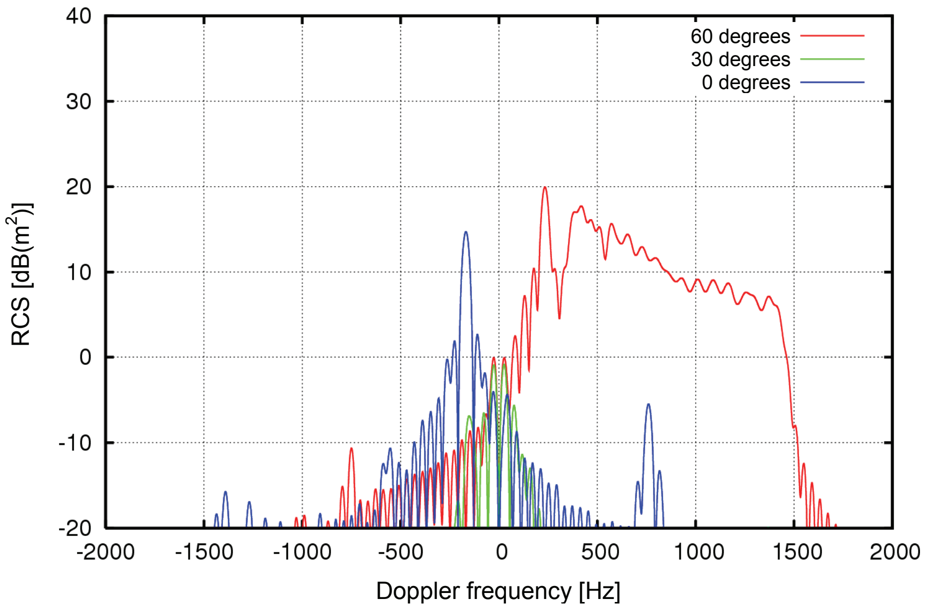


Fig. 13: Doppler spectrum at high speed of 19.5 rpm, rotor orientation of 90°

Wind turbine of 82 m with inner radar reflection reduction, orientation of 90°, VV polarisation, 19.5 rpm

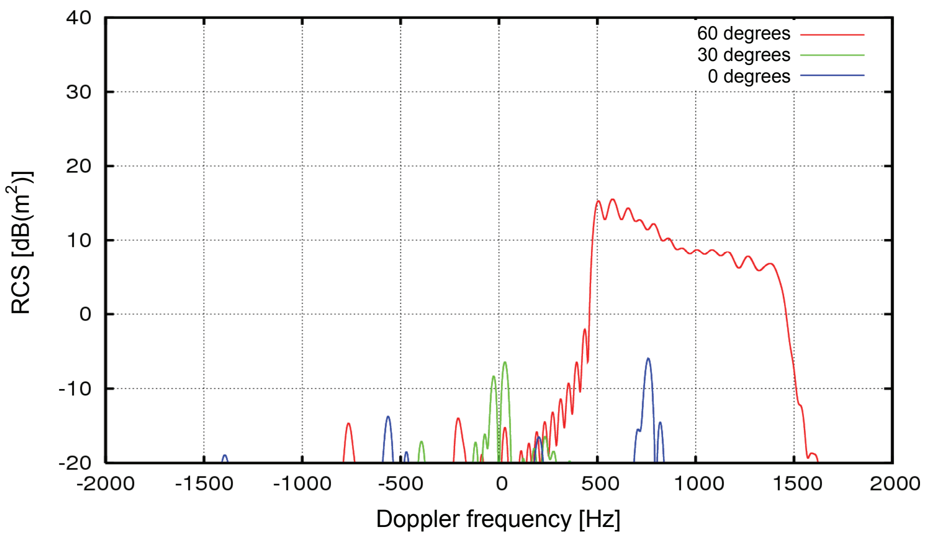


Fig. 14: Doppler spectrum at high speed of 19.5 rpm, rotor orientation of 90°

2.2.2 Potential for optimisation of wind turbines

The spectra of wind turbine radar echoes shown on the previous pages are standardised for the radar cross section (RCS) of the objects. The following applies in general: compared to objects with a large RCS, objects with a very small RCS rarely or never appear on the radar screen. As measures to reduce the RCS are also discussed here, it is useful to provide basic information on the definition of this term and the effect of the RCS on radar signals.

The RCS of an object such as a wind turbine is defined as the signal power reflected by this object relative to the signal power reflected by a ball with a surface of 1 m^2. It is therefore specified in m^2.

In general, the RCS depends on the material and the geometry of the object under observation, on its absolute size, its aspect angle and on the frequency of the radar signal. The RCS does not depend on the transmission power or on the distance between the object and the radar.

In the range of frequencies relevant to this study (around 3 GHz), the typical RCS values of aircraft is between 1 and 10 m^2, of vehicles between 10 and 100 m^2 and of wind turbines up to several thousand m^2. The RCS of all these objects, or more generally of all objects with a fairly complex structure, changes by a factor of several powers of 10 depending on the aspect angle.

Due to this very large dynamic range for the expected RCS values of various objects, the RCS is usually specified in dB(m^2). The dB scale is divided logarithmically with steps of 10 for a factor of 10, i.e.:

[m^2]	0.1	1	10	100	1000	…
[dB(m^2)]	-10	0	10	20	30	…

The RCS values of the terrain and the buildings in the environment of air surveillance radars are generally larger by several factors of 10 than the targets to be detected. These local signals and also others that do not change over time are removed from the radar echo signal using moving target filters. This process takes place internally in the radar unit – in the ASR-910 in simplified form and in the ASR-S via extensive algorithms – to ensure that targets can be displayed and identified successfully.

With analogue radars such as the ASR-910, decreasing the wind turbine RCS or the strength of the radar reflection results in the reduction of the frequency of appearance of the turbine on the screen. Reducing the spectral width of the Doppler information further supports the identification signal and data processing capabilities of advanced radars such as the ASR-S, thus suppressing wind turbine alarms and other unwanted appearances from the radar screen.

The frequency of appearance (or interference) of a wind turbine is determined by how often the rotating radar aerial is aligned with it, as well as by how often it reflects the radar signal with a sufficiently strong Doppler component for a sufficiently long period of time.

2.3 Potential to optimise the RCS of wind turbines

Wind turbines do not appear on radar screens due to their very high absolute RCS values, but mainly due to the nature of their echo signals, which varies with time as does their appearance on the screen.

The absolute magnitude of the RCS value is of particular importance at close range, up to a few nautical miles from the radar site, as the excessive strength of the signals received by the radar can overload the input, dazzling the radar and interfering with target detection.

In addition to investigating the high RCS values and their reduction with regard to the ASR-910, the investigations also covered the added effects induced by the dynamic RCS of the wind turbines and the behaviour of their echo signals, which do not vary with time on radars of the ASR-S type when using both measured and simulated turbine echo signals.

The computer models were specifically used to simulate a variety of measures on the wind turbines to reduce the radar reflections and thus their frequency of appearance on radar screens. The reflections relevant in this context do not only include surface reflections, but also multiple reflections resulting from signal components being reflected after penetrating into the rotor blade structure. The measures presumed here for the reduction of reflections from the surface of rotor blades offer solutions that are independent of the humidity and holds true for various weather conditions. This complies with other investigations performed in the United Kingdom.

It became apparent that decreasing the RCS of a wind turbine in the area of the blade root clearly reduced the frequency of appearance on the radar screen, while measures to reduce radar reflections from the tips of the rotor blades and from stationary parts of the turbine did not produce any significant results. The simulations indicated a reduction in reflections of approx. 20 dB compared to the unmodified construction.

For reduction of radar reflections near the root of the rotor blade, a clear restriction in the spectral spread of the echo signal was observed. This is the main factor for reducing the frequency of appearance.

It also became apparent that the effectiveness of measures to reduce reflections heavily depends on the rotor design, which varies considerably from manufacturer to manufacturer.

The following illustration indicates the relationship between the appearance of the turbine radar reflections and the respective display on the radar screen.

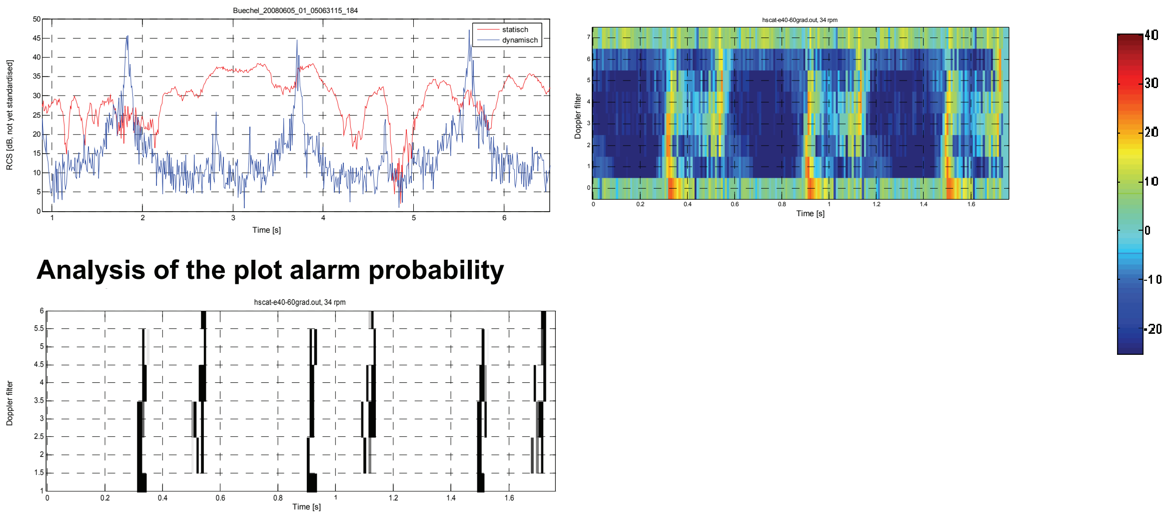


Fig. 15: Typical wind turbine display with ASR-S signal processing

The top-left diagram in Fig. 15 shows the wind turbine echo signal for one complete rotation of its rotor. It is divided into a static and a dynamic component. The red curve indicates the static component. It is defined as the part of the echo signal with a Doppler shift below a defined threshold (here approx. 100 Hz) corresponding to stationary or slowly moving objects. The dynamic component (indicated by the blue curve) comprises the part of the echo signal having a Doppler shift above said threshold.

In the top-right diagram the same received signals are depicted slightly modified as a false colour plot of the intensities in a time-Doppler diagram. The orthogonal axis shows the Doppler frequencies as measured by the ASR-S, i.e. the entire unambiguous measurement range with all the fold-over effects resulting from the radar characteristics. The intensity scale next to it shows the allocation of colours to signal levels in dB. The above-mentioned spectral extensions can be clearly seen in the area of the peak echo signal levels.

The bottom-left diagram in Fig. 15 illustrated the analysis of the probability of a plot alarm. It uses a binary representation to indicate which intensity peaks in the time-Doppler matrix will ultimately lead to a target alarm in the radar unit, if a typical signal detector is applied to this received signal.

It can be clearly observed here that the absolute signal level is not significant in triggering the display of a target, but rather the change in level compared to neighbouring objects of the matrix, indicting a change over time.

For this reason, it should be seen as a practical goal to avoid such strong RCS changes over time when designing rotor blades compatible with radar and when planning the corresponding measures to reduce radar reflections.

The slow speed of the rotors of larger wind turbines has a similar beneficial effect.

2.4 Perspectives for planning wind turbines when considering interference cells

The results clearly indicate the effect that rotor speed has on the Doppler characteristics and also the frequency of interference caused by a wind turbine. This fact provides the options described below for the future assessment of flight movements.

Assessing aircraft movements by considering interference cells as well as the frequency of appearance on the radar screen over the wind turbine area concerned is very useful to illustrate the interference. For this purpose, various flight paths are placed over the wind turbine area with the ability to track the aircraft being assessed in each case. The flight paths were placed in such a way to allow the assessment of both realistic and worst cases.

For assessing the flight movements, a flight speed of approx. 180 km/h was used as a basis, as specified by the military air traffic control service. At this speed, the target covers a distance of approx. 210 m while the radar aerial rotates once (requiring approx. 4.2 s for the ASR-910).

In the worst case, i.e. with a wind turbine interference of 100 % (very high rotor speed), tracking the target is no longer possible after more than two rotations of the radar aerial. For locating the aircraft again outside the interference zone, the target has to be reacquired, calling for at least two rotations of the radar aerial.

In this case, the wind turbine interference is classified as an impairment to an area under surveillance, which is defined by the resolution of the radar over distance and azimuth, centred on the wind turbine concerned. 100 % interference means that targets over this area are never visible on the radar screen.

The observations made on the ASR-910 indicate that continuous tracking of an aircraft is only possible if the probability of a wind turbine appearing on the screen is less than 20 %.

So far, no impairments to tracking targets due to wind turbines have been observed on the ASR-S. It is thus possible to track aircraft without interruption over the wind turbines visible from the Büchel radar site. The analyses performed at EADS in Ulm on the effect of wind turbine echoes on the internal signal processing indicated that impairments are nevertheless to be expected for extended wind turbine areas and that in this case, similar limits will apply to tolerable frequencies of appearance.

For all actual frequencies of appearance between “tolerable” and “intolerable” for a group of wind turbines, the effect on the tracking of aircraft can be calculated. In this context, account is also taken of overlapping areas affected by wind turbines located close to each other.

In the best case, i.e. with a frequency of appearance of less than 20 %, the radar does not lose the aircraft over the wind turbine area or is capable of recovering it immediately after it has left this area. This results from considering the probability of discovering an aircraft for each rotation of the radar aerial, taking the rules for the loss and recovery of a target into account.

In this way, low interference frequencies ensure that the difficult period of time when aircraft identification is restricted or impossible, is significantly shorter than the time required by the aircraft to cross the wind turbine area.

For military radars currently in operation, the identification of aircraft can be strongly supported by taking measures to reduce reflections on wind turbines. This provides a better basis for planning wind turbine plants, especially in the case of "repowering", if this means replacing several small systems with high rotor speeds by systems with lower rotor speeds.

Ideally, when combining measures to reduce reflections on wind turbines with the capabilities of modern radars, it will be possible to ensure uninterrupted identification during the entire flight of an aircraft over a wind turbine area.

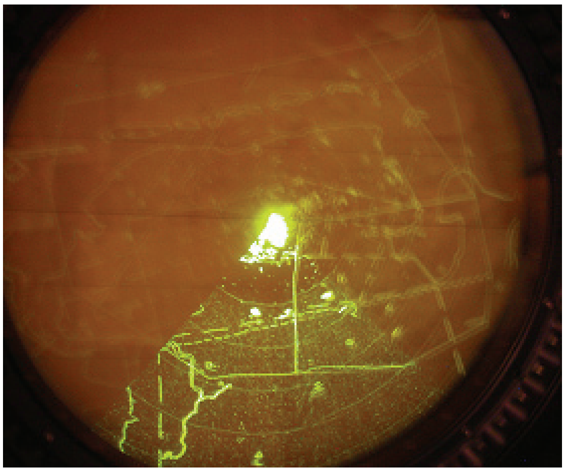
3 Investigation of interference to ASR-S

3.1 Survey of compatibility of wind turbines with ASR-S

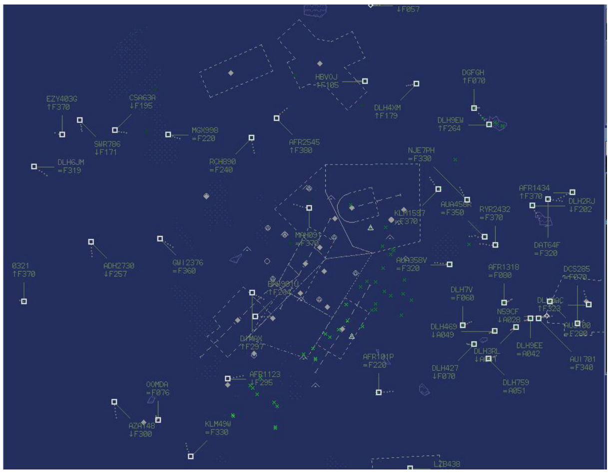
To assess the compatibility of wind turbines with the new ASR-S radar system intended to monitor air traffic at German military airfields in future, its characteristics were examined in detail by taking measurements on the existing prototype at Büchel. In addition to the analysis of the radar displays, data and signals were recorded to assess the performance of the individual stages of signal and data processing in the ASR-S system (familiar within EADS).

These radar measurements serve several purposes:

- Survey of the possible interference that wind turbines could cause to ASR-S
- Check the effectiveness of the ***current*** ASR-S signal and data processing for compatibility with wind turbines
- Record wind turbine signatures to validate the above-mentioned computer model calculations for their reflected signals
- Record signatures for the development of algorithms for a future "Wind Turbine Modification Kit", which should increase the compatibility with wind turbines of such air traffic control radars, as a retrofit package



ASR-910:
No tracker
(human observer)



ASR-S: two primary radar trackers (channels A, B), secondary radar tracker, sensor fusion, linked to other radars

Fig. 16: Analogue and digital radar

Fig. 16 shows the essential difference in the display of purely analogue ASR-910 radar used to date, and the modern ASR-S radar with digital signal and data processing. Radar operating on analogue principles indicates to the air traffic controllers the echo signals from possible aircraft as spots of light at the moment that the radar beam sweeps past (illustrated by the picture on the left). In the illustration, the long exposure time allows a sector of approximately 60° to be seen on the display, corresponding to an observation period of approx. 0.7 seconds.

In contrast, the digital display of a modern radar system constantly indicates the information about all possible aircraft using different symbols and/or colours, depending on the measurement state and the classification by the radar unit.

The following signal and data processing methods are useful to improve compatibility with wind turbines – having been confirmed by other investigations performed on an international basis – and have therefore already been incorporated into the ASR-S:

- The **"Doppler Clutter Map"** (DCM) reduces the plot density of objects that cause echo signals with Doppler shift, but have a static location
- The **"Traffic Map"** (TM) catalogues the areas with increased plot density in the radar. Plots occurring in these areas are subject to special treatment and classified as "traffic" or "aircraft" on the basis of their measured characteristics
- The **"Short Track Initiation Map"** (STIM) catalogues the areas where, despite the above-mentioned measures, the plot density is so high that initialising new "tracks" presents a problem. In these areas, increased requirements are placed on the quality of the plots for the initiation of a track

All these measures serve to reliably track aircraft, even in the absence of the secondary radar signal. Normally, the secondary radar alone provides sufficient information to track an aircraft. It is however required that a transponder be installed.

The compatibility of wind turbines with secondary radars was not investigated during this project. From the ASR-S system at Büchel, no interference to the secondary radar caused by wind turbines has been observed, nor is expected.

Thus far the observations made by the air traffic controllers at Büchel have ***not*** shown any impairment to tracking aircraft flying over the local wind turbine areas, with this tracking process being automatically performed by the ASR-S. The air traffic controllers therefore do not see any interfering wind turbines on the radar screen, although turbine echo signals can certainly be detected and plotted within the ASR-S.

For the purpose of testing the measures implemented under particularly difficult conditions, a small aircraft flying at low speed and at low altitude along a circular course over a wind turbine area near Büchel was tracked using the ASR-S. The results of this measurement emphasise the excellent performance of the ASR-S when tracking targets over wind turbine areas, as is shown by the following illustration.

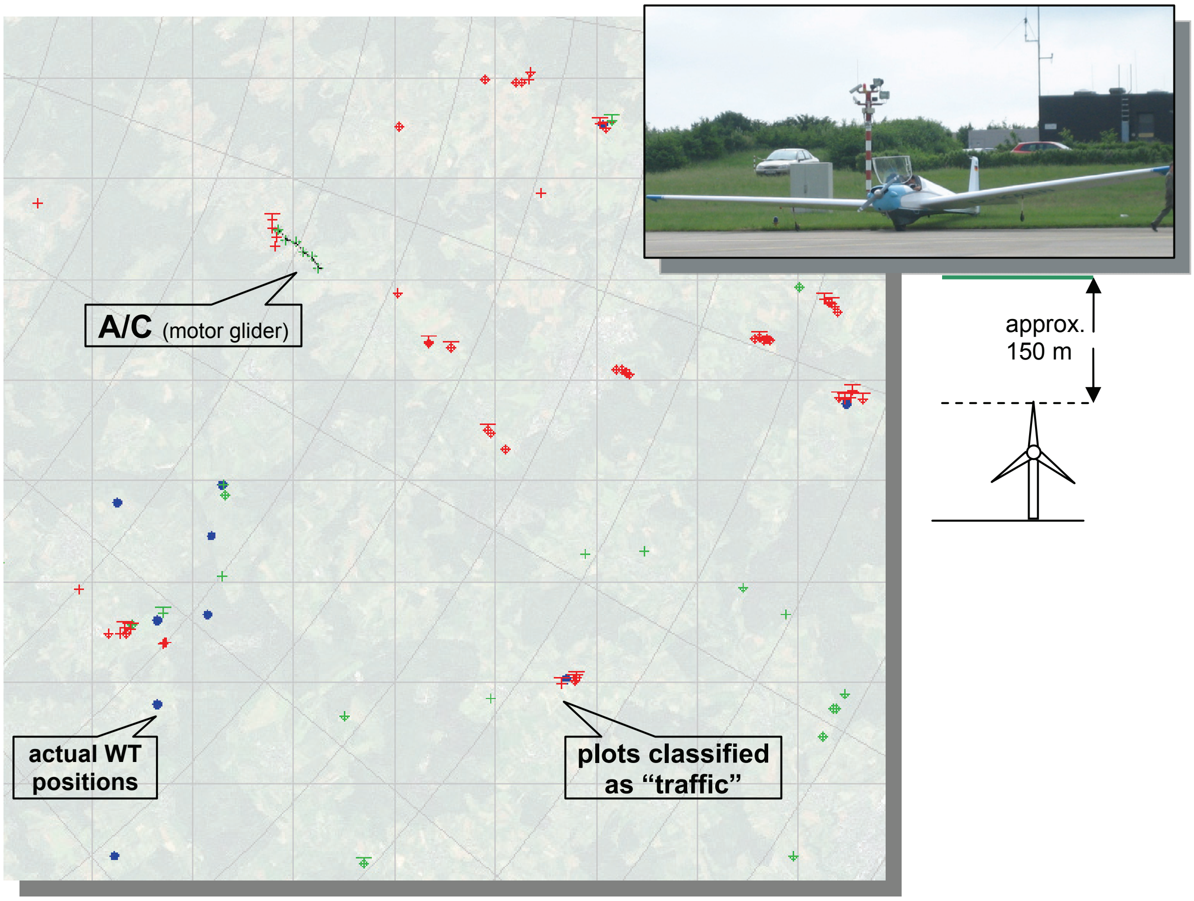


Fig. 17: The display of internal alarms in the ASR-S when tracking aircraft

The above map section shows internal plot and track results for the ASR-S.

Green symbols:	Plots that can be used to produce a track as a possible aircraft
Red symbols:	Plots that have been classified as “traffic” (i.e. moving ground objects) and are given a low priority or are not used to produce a track
Blue dots:	Positions of known wind turbines that were subsequently added to the illustration (they are not available in the ASR-S)
Black lines:	Current tracks with a “history” (here from 5 rotations of the aerial)

3.2 *Potential to optimise the ASR-S radar*

Following the implementation of the above-mentioned set of measures into the ASR-S radar to improve the compatibility with wind turbines, several other areas providing distinct opportunities for improvement have been identified. This includes in particular the effects that could be expected from wind turbines located in wind parks much larger than those around Büchel.

These areas have been systematically investigated, the possible modifications to improve compatibility with wind turbines have been designed and their effects on compatibility have been assessed. It is described in detail in the sections that follow.

3.2.1 Adaptive antenna characteristics

The receiver design of the ASR-S primary radar provides the option of electronically altering the elevation of the antenna’s radiation pattern by making changes to the shape of the aerial module and adding some analogue electronic components to the receiver. This alteration, which depends on the distance and azimuth angle, allows the radar beam to be “lifted” over extended wind turbine areas (wind parks), while still being able to capture signals from objects that are flying close to the ground before and after these areas. This ensures the following:

- Avoiding or reducing target echoes being obscured by reflections from wind turbines
- Avoiding receiver inputs being overloaded due to wind turbines at close range
- Maintaining the radar sensitivity in the airspace to be monitored

The following illustration shows the principle of this process. The red line represents a limit in the sensitivity of the receiver characteristics at a certain elevation; above this line the receiver sensitivity is high, below this line it is low (the radar sensor is at the origin of the coordinates).

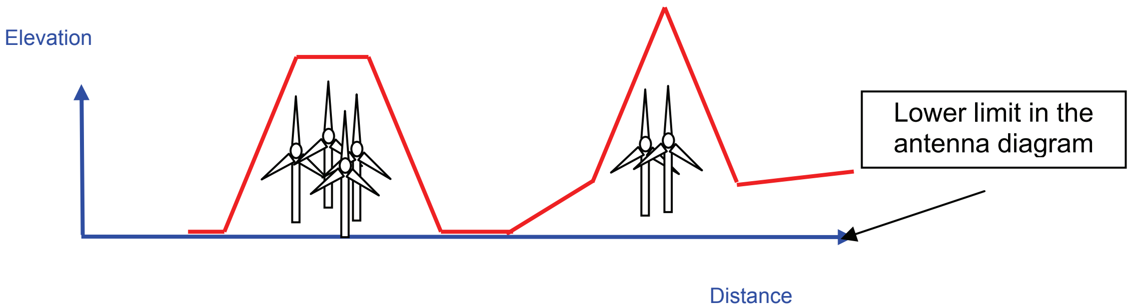


Fig. 18: The principle of electronic beam scanning

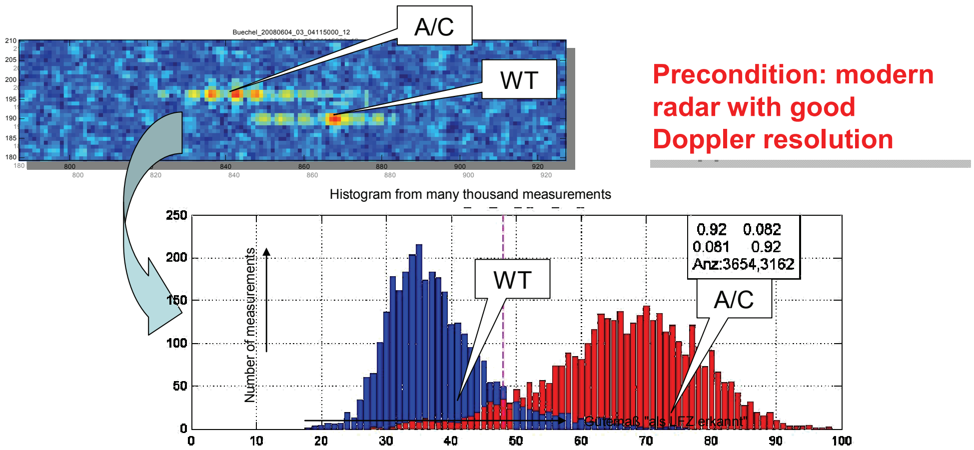
3.2.2 Signature classification

Signature classification is a method to classify the origin of the signals received based on their appearance.

In contrast to the above-mentioned classification in the traffic areas, classification is performed on the basis of extracted parameters, such as speed and plot.

Signature classification analyses the time-varying Doppler spectrum within one aerial sweep over the detected object. From this spectrum, a series of special characteristics are extracted that are defined in such a way as to differ as much as possible for objects from different origins. These characteristics are then fed into a statistical classifier.

Signatures in the received radar signal (a measurement, example)



⇨ **The signature classification reduces the burden due to wind turbine plots on radar screens by approx. 2/3 without degrading the capture of targets**

Fig. 19: The principle of signature classification

Fig. 19 illustrates this principle. The assessment of several thousand signatures of wind turbines and aircraft from the recordings made at Büchel shows that approx. 2/3 of the plots of wind turbines can be suppressed without any appreciable impairment to the target acquisition performance. If a loss of 10 % in the acquisition of targets can be accepted, it would even be possible to suppress 90 % of the wind turbine signatures. However, a loss of 10 % is not acceptable in practice.

In practice, no fixed threshold for the suppression of plots will be selected. Instead, all plots will be assigned a quality parameter that measures the reliability of the estimated alarm origin, i.e. whether the plot was caused by an aircraft or a wind turbine. The lower part of Fig. 19 shows the histograms of this quality parameter for the two classes mentioned, with the performance of the classification system being assessed based on the overlap of the histograms.

3.2.3 Adaptive tracking methods

The task of the tracker is to take the snapshots of the target alarms (i.e. the plots) from several rotations of the aerial and to combine them to form tracks.

This results in a significant reduction in the display of alarms on the radar screen, by restricting the display to aircraft that actually exist, after capturing their position several times and determining the data about their path, i.e. 2D position and speed.

For the generation of tracks, the ASR-S sensor tracker has access to the following input data:

a) Plots from two independent reception channels

b) Messages from the secondary radar (transponder interrogations)

c) Plot messages from neighbouring air traffic control radars

This information is merged by the sensor tracker to produce a view of the overall situation and is considered when generating the tracks.

In addition to the existing algorithms that produce tracks from the specified input data as well as from models and filters for possible flight movements of the targets, the results from the signature classification and information about the limits and the currently possible interference from wind turbine areas may also be used.

It could be demonstrated that with the new methods discussed here, it is even possible to track aircraft over areas with high density of wind turbines.

As an example, the following illustration shows the result of a simulated flight over a wind turbine area, with the aircraft changing its direction over this area.

For this an aircraft without a transponder was simulated, using single channel operation on the primary radar, corresponding to the worst case (difficult conditions) in radar operation.

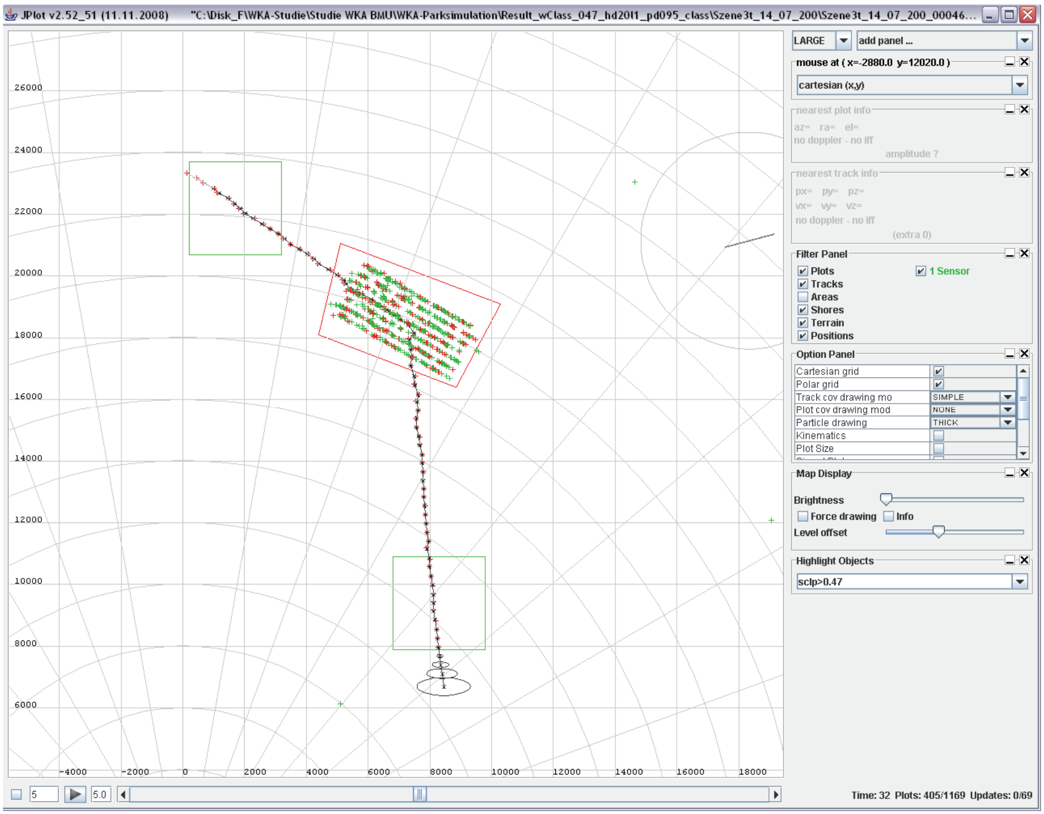


Fig. 20: The track of a complete flight over a wind turbine area

The figure shows all the plots and track-updates for approx. 50 sweeps of the aerial over the scenario. In this illustration, the aircraft started its flight over the wind turbine area in the green box at the top-left and ended in the second green box in the middle at the bottom. The limits of the wind turbine area are marked in red.

Individual plots are shown in red or green, depending on the result of the signature recognition process, where red indicates “recognised as an aircraft”.

Track updates are shown as black crosses on the corresponding plots. If the track cannot be updated because of a missing plot, then instead a circle will show the expected window for the next plot update and the track will use a prediction. For this reason, after the flight was aborted, there is a funnel of expected areas with increasing size at the end of the track, before it is finally interrupted.

Such flights over wind turbine areas were carried out with variations in the type of turbine, in the geometry of the installation and in the wind park density as well as variations to the flight direction, speed and manoeuvres of the aircraft. The aim of this investigation was to determine the conditions at the limits to tracking aircraft over wind turbine areas, exclusively using the primary radar.

This essentially produced the following results:

- Tangential flights are significantly more critical than radial flights
- Slow aircraft are more critical than quick aircraft
- The interference caused by wind turbines is ***not*** proportional to the wind park density

  (This is a surprising result and the exact dependencies still have to be investigated in more detail)
- The classification of wind turbines makes a major contribution to the reliability of tracks

3.3 Implementation options for the ASR-S

The above-mentioned potential to optimise the radar compatibility can be implemented using the Wind Turbine Modification Kit defined in this project.

The purpose of this kit is to create the same compatibility with wind turbines in extensive wind parks that was observed in the moderately spread-out turbine area near Büchel. Some of the future ASR-S sites already cover such extensive wind parks.

The kit comprises the “ES aerial”, i.e. the antenna with electronic beam scanning in elevation, as well as the signal & data processing unit, which includes the new or modified classification and tracking methods mentioned above.

The design of the Wind Turbine Modification Kit as a separate package of equipment and measures, ensures that existing ASR-S radars can be updated to become “ASR-ES” systems.

In principal, this kit can also be used for modernising third-party equipment. For this, however, special adaptation development will be required in each individual case.

The signal & data processing components of the kit, in particular for signature classification, can also be used in air surveillance radars (i.e. 3D radars). However, investigating 3D radars fell outside the scope of this project.

4 Summary

The results of the study show what mechanisms in the interaction between primary radars and wind turbines mostly affect the display and identification of aircraft on the radar, and how such interference can be calculated in advance, and subsequently reduced or even avoided. In this context, the frequency of interference caused by a wind turbine is of special importance.

The corresponding assessment method takes into account the radar characteristics that are relevant to the interference in its area of operation, and of the wind turbines, including their location in the terrain. This procedure is described in more detail in the following sections and is intended to be used as the basis for the approval process for wind turbines. It allows determining the actual interference caused by the wind turbines on the existing ASR-910 and ASR-S radar systems as well as on the ASR-ES system currently being developed for optimised compatibility with wind turbines.

With the new assessment method, based on observations and provable calculations, it can be ensured that applications to build wind parks will always be judged on the same basis and that decisions about implementation will always be consistent. At the same time, the free space between wind turbine areas can now be set to the size that is actually required from a technical perspective. This means that additional safety distances required due to lack of understanding of the problem can be reduced.

4.1 Basis for assessments in the approval process

The assessment of plans submitted for approving the construction of wind turbines in the vicinity of radars is expected to be supported by a structured and standardised set of “Guidelines for the Assessment of the Effects on Air Traffic Control and Radars” as a check list. This should ensure that the assessment of planning applications is consistent and is supported by the results of up-to-date measurements and analyses of the RCS of wind turbines as well as by comprehensive radar observations using radars in normal operation.

This will enable an expeditious and legally robust assessment that will offer additional approval options taking low reflection wind turbines into account. This refers not only to existing ASR-910 systems, but also to the systems with extended functionality such as the ASR-S and the ASR-ES (an ASR-S that has been enabled to deal with the problem of wind turbines using a modification kit).

The technical basis for assessment uses air traffic control parameters such as the speed and direction of aircraft.

Depending on the results of the assessment with regard to air traffic control and the radar involved, a subsequent operational assessment may also be required. At present, no relevant parameters have been identified that would be suitable as criteria for the erection of wind turbines.

In addition to the different interference effects of wind turbines as moving objects with varying radar reflection characteristics, the technical criteria mentioned below include the impact of the topography, the basic technical parameters of the current ASR-910 radar systems as well as the advanced future radar systems with digital data and signal processing capability.

1. **Classification of wind park planning for building applications/enquiries (robust criterion)**

   At this point, the documentation must present a detailed description of the project and system, including a description of the wind turbine dimensions and materials. In addition, any existing wind turbines located in the immediate vicinity also have to be specified.

2. **Consideration of the terrain and obstructing topography as well as operational conditions (robust criterion)**

   When the approval authorities assess the application, the environmental conditions have to be included.

3. **Consideration of the characteristics of the radar sensor (robust criterion for ASR-910 and ASR-S)**

   When assessing the application, the technical parameters of the existing and any future radar systems have to be considered.

4. **Consideration of the arrangement of interference cells in the area (robust criterion)**

   When assessing the application, the effects of the interference cells as well as the individual frequency of interference caused by the wind turbines and the density and overlap of the interference cells have to be considered.

5. **Determination of the flight path scenarios or the directions that aircraft fly over a wind turbine area (robust criterion)**

   When assessing the application, the flight path scenarios and the directions that the aircraft fly over a wind turbine area have to be considered as representative of all possible air traffic situations that may occur.

6. **Assessment of the interfering effects of wind parks (robust criterion)**

   The assessment of the results has to consider all of the above-mentioned aspects.

7. **Radar reflection reduction measures for wind turbine rotor blades (currently not a robust criterion)**

   In addition to the above-mentioned aspects 1 to 5, the supplementary assessment of the results has to also consider measures to reduce the interference caused by wind turbines.

8. **Effect of signal and data processing options in a radar system (currently not a robust criterion)**

   In addition to the above-mentioned aspects 1 to 5 and 7, the supplementary assessment of the results has to also consider signal and data processing measures of future radar systems to reduce the interference caused by wind turbines.

When considering modern digital radar detection systems, each proceeding step of the assessment differentiated between legally robust criteria and criteria that are currently not robust. The same applies to the assessment of optimisation measures on wind turbines.

The benefits of the assessment guidelines as well as future extensions to these are:

- Legal safeguards by using robust criteria for technical assessment
- Standardised approach (transparent processes that are easily understood, even by third parties)

The relevant influencing factors that resulted from the investigations described above and that are explained in the basis for assessment are the following:

- Wind turbine factors
  - Installation geometry, arrangement, alignment, density
  - Separation distance from existing wind turbines or wind parks
  - Design of the wind turbine
    amongst other aspects, the rotor dimensions and speed, the materials used and the lightning conductor system
  - RCS of the wind turbine
    amongst other aspects, peak values, Doppler spectrum, time variance

  - Frequency of interference due to the wind turbine and its effect on aircraft identification

- Topography of the terrain, including all natural and artificial obstructions, e.g.:
  - Layout, alignment and density of existing wind parks

- Radar-relevant factors
  - Resolution (radial, azimuth)
  - Rotational speed of the aerial
  - Maximum receiver input level
  - Filtering process during signal and data processing
  - Tracking method

- Factors associated with flight operations
  - Flight direction
  - Flight orientation
  - Flight speeds

The interference is assessed by defining so-called “interference cells” from the wind turbine locations and the resolution characteristics of the radar. These cells are areas where the turbines are expected to influence the received radar signal.

All of the above-mentioned parameters influence the extent of interference to be expected in these interference cells. To calculate these parameters require specialist skills in the field of radar and radio frequency technology. These skills cannot be replaced by an assessment catalogue.

The characteristic differences of the radar types ASR-910, ASR-S and ASR-ES (ASR-S with the Wind Turbine Modification Kit, refer to section 3.3) as noted in the basis for assessment, result in different interference levels in what are otherwise identical scenarios.

For the ASR-910 and ASR-S radars, it is currently possible to calculate interference using the assessment catalogue since all their above-mentioned radar parameters have been proven and in a legal sense are therefore robust.

The ASR-ES radar is still in the concept phase. Therefore its radar parameters are currently considered to be provisional.

4.2 Examples for arrangements and flights

The illustration on the next page shows an example of various flight scenarios and describes the effect of interference frequency and interference cell size of wind turbine systems in these scenarios.

Depending on the location of the radar, the size of the interference cells increases in proportion to R (resulting in a degradation of the spatial resolution for a constant angular resolution).

The interference disappears when the wind turbine is below the “radar horizon” value.

For a radar aerial that is 35 m high and for a wind turbine having its hub at 150 m, the *visual* horizon is at a distance of approx. 20 nm (37 km).

Compared to the *visual* horizon, the *radar* horizon could be at a different distance, e.g. due to the diffraction of electromagnetic waves. This means that the radar horizon could be at a significantly larger distance than the visual horizon. However, buildings, terrain and/or vegetation may significantly reduce the distance to the radar horizon.

It is thus necessary to determine the radar horizon (= line-of-sight) for each case.

In the area around and beyond the radar horizon, the interference is significantly reduced, with the frequency of appearance being decreased although the size of the interference cell remains the same. For frequencies of appearance below the observed frequency of interference or interference limit (e.g. 20 %) the size of the interference cell is no longer relevant.

When changing from the ASR-910 to the ASR-S, the interference cells are *not* reduced in size (the aerial aperture in azimuth is almost the same). For the ASR-ES, the interference cell is the same in azimuth, but somewhat smaller over distance (i.e. along the line-of-sight between the radar aerial and the wind turbine).

The beam scanning process of the ASR-ES system ensures that the frequency of appearance of wind turbines is reduced and is more likely to fall below the threshold of interference.

In addition to this, as the distance from the airfield increases, the need to continuously track aircraft should reduce.

(Operational criterion)

Flight paths over wind turbines:

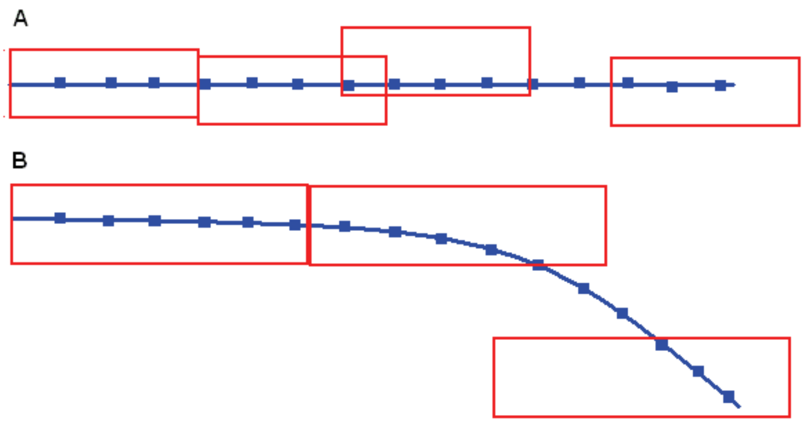


Fig. 21: Flight scenarios

Case A:

This situation presumes a straight flight path over the wind turbine area at a medium distance from the radar location. As the aircraft flies over the first 3 wind turbines, identification of the aircraft is increasingly impaired. The gap between the third and fourth turbines is advantageous, but may not be sufficient.

Flight paths cutting diagonally across the arrangement of turbines are significantly less critical.

Case B:

By presuming a flight path that is not straight, an unfavourable situation would be created by the wind turbine arrangement. Case B shows increased interference zones for the individual wind turbines due to their great distance from the radar location. For such cases, measures to reduce the reflections of the turbine in the centre or a lower speed turbine could benefit the entire arrangement by not critically extending the loss of aircraft identification that resulted from the flight over the first turbine. The time to fly over the third turbine is not long enough for the aircraft identification to be lost again.

5 Summary & recommendations

Options have been identified and demonstrated that determine the interference caused by wind turbines to air traffic control radars in real scenarios.

In particular, the frequency of interference occurrences caused by wind turbines in individual scenarios was recorded and evaluated under operational conditions. A good set of data was obtained as a result of the large number of wind turbines investigated at various military airfields. The advantages of large wind turbines over smaller units due to their slower rotation speed could be demonstrated for the turbines investigated.

A basis for assessment was produced that allows interference to be determined.

The compatibility with wind turbines of the three radar categories mentioned (ASR-910, ASR-S and ASR-ES) is significantly different. Therefore the assessment of compatibility should also take the time period that each type of radar will be used at the location concerned, as well as the time when each planned wind turbine will come into operation into account.

According to the current schedule, the first three ASR-S systems are expected to come into service in 2011. This includes the unit for the North German airfield at Wittmund. During the following years up to about 2015, all the ASR-910 radars will be replaced by the new ASR-S systems. If and to what extent ASR-ES systems will be procured instead of ASR-S systems, or if ASR-S systems will be updated to ASR-ES systems, was unknown at the time of writing.

Measures were also defined that could significantly reduce the effects of wind turbines on air traffic control radars. These measures were tested in simulations and measurements. From this it became clear that a package of measures is required, consisting of:

- Design and construction of future wind turbines taking radar requirements into account, in particular using a design that minimises the RCS for the frequency range around 3 GHz. Owing to their lower rotor speeds, many of the latest generation wind turbines (as extensively explained above) already have better compatibility with radars compared to older units that are intended to be replaced as part of “repowering” measures.

- Measures on the radar systems to improve compatibility with wind turbines. A package of measures has been defined and assessed for its performance in improving compatibility with wind turbines. This package is based on the current technical version of the ASR-S air traffic control radar. As a modification kit for existing systems, it can significantly improve the compatibility. This was proven by measurements on the ASR-S and by computer simulations.

Remark: The radar modification kit enhances the ASR-S to an ASR-ES system with optimised wind turbine compatibility. In principle it may also be used for other modern air traffic control radars. In these cases, similar improvements could be expected if the performance parameters of the radars concerned are similar. The modification kit to optimise compatibility with wind turbines is also suitable to enable 3D air defence radars to deal with the problem of wind turbines (however excluding the electronic beam scanning aerial).

It is recommended that the investigations be continued to more precisely determine the characteristics of measures to reduce radar reflections of wind turbines on the one side and the effectiveness of measures to increase ASR-ES compatibility on the other. Such additional investigations should be performed as part of a follow-up study.

During such a follow-up study, manufacturers of wind turbines and in particular of rotor blades, should be actively involved with the aim of actually implementing the measures to reduce radar reflections by a wind turbine in the vicinity of ASR-910 and ASR-S systems. This will allow assessment of the change in the effect that this modified wind turbine has on the radar systems.

Abbreviations and terminology

2D 2D radar: measurement of distance and azimuth

3D 3D radar: measurement of distance, azimuth and elevation

Alarm Here in the radar unit: general term for the occurrence of messages inside the system about objects that may need to be tracked

Algorithms Mathematical methods to calculate information. In the system this is mostly implemented in the (⇨) SW. The algorithms determine the “intelligence” of the system

AntUk Lower edge of the aerial

ASR Airport surveillance radar

ASR-S ASR production unit from EADS

ASR-ES ASR-S type radar fitted with a wind turbine modification kit to increase its compatibility with wind turbines

Detection Occurs when the level of the radar echo signal crosses a predetermined threshold value. Detection is the first stage in the radar’s (⇨) alarm chain

DCM Doppler clutter map, which is a measure to avoid plots from false targets

Doppler shift Effect of a frequency shift when radar waves are reflected from a moving object

Doppler spectrum Display of the signal level from an object along the (⇨) Doppler shift axis

Far field Area of an electromagnetic field where calculations supposing a planar wave-front are justified. For the radars considered here, far field conditions apply from a distance of several 100 m to a few 1000 m to the radar. Considering the wind turbines as emitters leads to significantly greater distances than for the far field condition

GCM Ground clutter map, which is a measure to avoid plots from false targets

GND Height of the terrain

HMM Hidden Markov model ⇨ HMM classifier

HW Hardware (system components)

IMM Interactive multiple model: special type of tracking algorithm to minimise measurement errors with a quick reaction time

A/C Aircraft

Modification kit HW & SW package to improve the compatibility of air traffic control radars with wind turbines

MoM Method of moments, which is an analytical process for the spread of radio frequency signals

MPR — Type designation of an air defence radar unit

MTD — Moving target detection: detection of a moving target with measurement of the line-of-sight speed, normally on the basis of digital signal processing

MTI — Moving target indication: detection of a moving target without resolving the target speed, which is typical for older radars without digital signal processing

Plot — A single radar (⇨) alarm on the basis of (⇨) detecting an object that was illuminated once (one sweep of the aerial)

PPI — Plan position indicator

PSR — Primary sensor radar

RASS — Process / tool to measure and assess radar systems

RCS — Radar cross section

Range reduction — Measure for a limit to, or a reduction of the radar visibility in a defined section of air space. A value of 100 % means that there are ideal operating conditions

BSCS — Back scattering cross section: reflected radar echo level, specified in m^2 or $dB(m^2)$

$BSCS_{dyn.}$ — Dynamic BSCS: parts of reflections from moving objects which change over time

SSR / IFF — Secondary surveillance radar / identification friend or foe

ST — Sensor tracker

STC — Sensitive time control: time dependent control (here: amplification) during the reception of the signal

STIM — Short track initialisation MAP: measure in the ASR-S system to avoid false tracks

SW — Software (programmed procedures and methods for signal and data processing)

Track — Automatic detection of a target's position and movements on the basis of several (⇨) plots

UTD — Uniform theory of diffraction: process to analyse the spread of radio frequencies

WT — Wind turbine

WT modification kit — Package of measures with HW & SW modifications for air traffic control radars to improve their compatibility with wind turbines

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/4/ Discussion and EADS BRE presentation in EUROCONTROL / Wind Energy Task Group of 1 March 2006: “Potential effects of wind turbines and justiciable solutions”

/5/ EADS BRE final report: The effects of obstructions on guidance equipment using RF signals, of 15 February 2004

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