WINDFARM CHARACTERISTICS AND THEIR EFFECT ON RADAR SYSTEMS

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Abstract

Generating electricity from renewable energy sources is a major part of the UK Government's strategy to tackle climate change and to develop business opportunities. It has set ambitious targets of generating 10% of all UK's energy from renewable sources by 2010 with an aspiration to double this by 2020 [1]. Wind energy is expected to be a key contributor to these targets. There are concerns, however, that the construction of windfarms will have a negative effect on both Air Traffic Control (ATC) and Air Defence (AD) radars and many windfarm developments fail due to objections from radar stakeholders. This paper explores the effects, on radar system components, of the echo signals received as a result of radar illumination of a windfarm and their impact on the overall performance of a radar system.

1 Introduction

This paper commences with a brief description of some important physical characteristics of wind turbines, and windfarms, their proliferation across the UK and the concerns both real and imagined of key radar stakeholders. The main body of work deals with the effects of windfarm echo signals on the performance of radar systems and concludes with a summary on the major impacts on radar operation.

2 Windfarm proliferation

As a result of the UK government's renewables obligation, there has been considerable windfarm development in the UK in recent years. Deployment has spread across the UK both on- and off-shore. At the time of writing, a total of 147 windfarms with a capacity of ~2.2GW are operational. A further 38 are under construction with a capacity of ~1.3GW, 91 are consented and 234 are in planning [2], this does not include those in the early stages of planning but not yet submitted into the formal process. Should all of these become operational there would be a total of 7310 wind turbines with a combined capacity of >18GW. Figure 1 is an up to date map of windfarm locations.

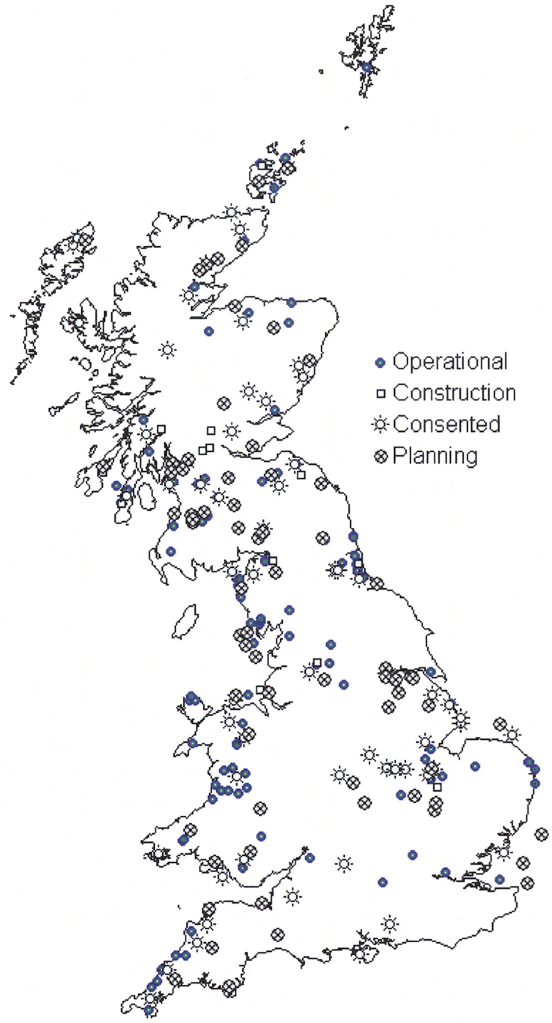

Figure 1: Map of UK windfarms and their status [2]

3 Wind turbine and windfarm characteristics

There are a number of different turbine manufacturers producing a variety of turbine types. However, all modern turbines typically have a very similar physical configuration, consisting of tapered cylindrical steel tower topped by a nacelle, supporting three aerodynamic blades, as illustrated in Figure 2. Table 1 lists typical parameters of modern designs.

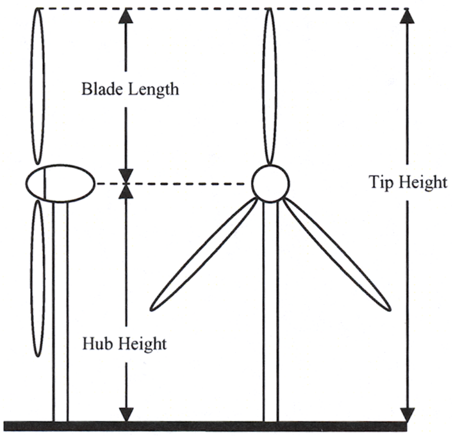

Figure 2: Physical configuration of a typical wind turbine

Turbine rating (MW)	1.5 [3]	3 [4]	5 [5]
Blade Length (m)	38	45	62
Hub height (m)	60-110	80-105	100-120
Tip height (m)	98-148	125-150	162-182
Rotation rate (rpm)	17	16	12
Max Tip speed (m/s)	68 (132kts)	76 (147kts)	79 (155kts)

Table 1: Typical wind turbine parameters

Electromagnetic modelling in the S-band (2.7 - 2.9GHz) and the L-band (~1.3GHz) operating frequencies of the radars in question has indicated that the peak Radar Cross Section (RCS) of turbines of similar dimensions to these can be as much as 300 000m^2 (55dBm^2) total. Turbine blades on their own can have a peak RCS of 30 000m^2 (45dBm^2) each [6], [7].

The RCS of any irregularly shaped target varies with its orientation with respect to the radar, in the case of an individual wind turbine, the orientation of the blades will be continually changing with respect to the radar, this means that while the average RCS may be lower, there will often be times when a blade is oriented to give close to its peak RCS and thus 'glint'. For a large number of wind turbines grouped together into a windfarm, different turbines will 'glint' at different times and the windfarm will appear to the radar as a collection of randomly glinting objects with large RCS. For comparison small fighter jets may have an average RCS of only around 1 - 10m^2 (0 -10dBm^2). Of particular importance is the velocity of the moving blades; the maximum tip speeds are in the same range as slow moving air targets such as landing commercial aircraft, general aviation aircraft and helicopters - all of which are wanted targets for many radar applications. At certain orientations turbine blades will impose considerable Doppler shift on returning radar pulses as predicted in [7] and measured in [8].

4 Affected radar

The radars most affected by windfarm interactions are typically of the long range surveillance type, since they operate over extended ranges. These include both en-route and terminal manoeuvring area ATC radar and Air Defence radar. In the UK ATC radars are typically situated at or near to airfields, however, a number of en-route radars are sited in other locations, such as hill tops, to provide good long range cover. Air Defence radars are typically sited near to the coast.

5 Radar stakeholder concerns

The main radar stakeholders include the civil Air Traffic Control and the military Air Defence communities. Civil ATC users are mainly concerned about potential windfarm clutter detections since these could be perceived by ATC operators as aircraft or obscure genuine aircraft detections. This could compromise their safety obligation to maintain safe aircraft separations. As well as ATC concerns similar to their civil counterparts, the UK MOD is also concerned with possible radar desensitisation, which could reduce their capability to detect clandestine approach to the UK and compromise Homeland Air Defence operations [11].

In order to investigate these concerns a number of radar / windfarm trials have been conducted using either ATC or AD radar sensors ([12], [13], [14]). These have investigated the effect of operational windfarms on radar performance. Observed effects included:

- Clutter: Increased number of unwanted returns reported in the area of windfarms due to the detection of wind turbine echoes.
- Desensitisation: Reduced probability of detection for wanted air targets in a region extending above and around windfarms in both range and azimuth.
- Consequent loss of wanted target plotting and tracking performance in the affected areas

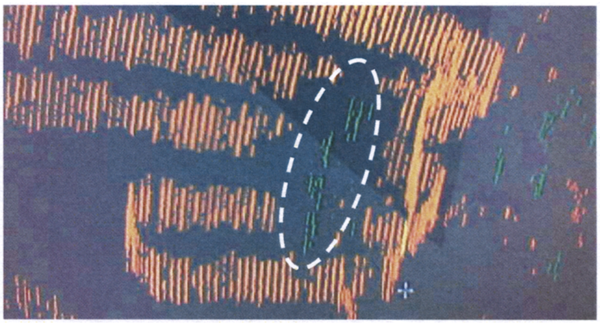
Figure 3: Aircraft time history and windfarm clutter (circled) [13], note the desensitisation around the wind farm

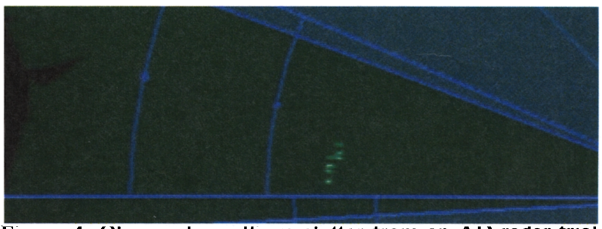
Figure 4: Observed windfarm clutter from an AD radar trial, post ground clutter filtering [14]

6 Impact on radar systems

The causes of these observed effects can be related to various aspects of radar system and sub-system design. These are outlined in this section.

Figure 5 is a block diagram of a typical surveillance radar system design; Table 2 outlines the functions of the various sub-systems.

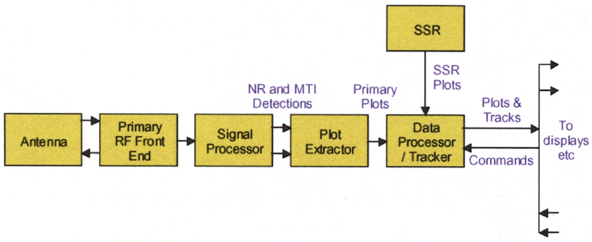

Figure 5: Radar system block diagram

Antenna	Either shaped reflector or phased array
Primary RF Front End	Transmitter(s), Receiver(s), Duplexer etc.
Signal Processor	Extracts signal information about wanted targets whilst rejecting undesired signals (clutter). Normally implemented digitally, this function usually comprises Analogue to Digital Conversion, Pulse Compression, Clutter Filtering, Integration Processing and Constant False Alarm Rate Detection Processing.
Plot Extractor	Calculates position of targets and associated properties based on detections output by Signal Processor. Output in the form of 'Plots'
SSR	Secondary Surveillance Radar, estimates the position of co-operative targets based on transponder replies
Data Processor / Tracker	Carries out scan-to-scan plot association and forms target tracks. More complex systems may also fuse data from other sensors (e.g. SSR), attempt target recognition and/or carry out more sophisticated data processing algorithms tailored to the systems' properties and environment.

Table 2: Radar sub-system descriptions

6.1 Antenna

6.1.1 Azimuth sidelobes

An unavoidable feature of antenna designs are sidelobes where a radar is sensitive (at a lower level) to returns arriving from off boresight directions. A typical one-way azimuth pattern is illustrated in Figure 6.

Since wind turbines present such large targets they may still be detected by a radar via these sidelobes. Even if they are not detected in the sidelobes, for 55dBm^2 RCS turbines, 1m^2 RCS targets and a required radar target-to-clutter ratio of 15dB, two-way sidelobes must be <-70dB (-35dB one-way) in order to avoid desensitisation. Figure 6 indicates that the azimuth angle required is ~3° either side of the beam peak.

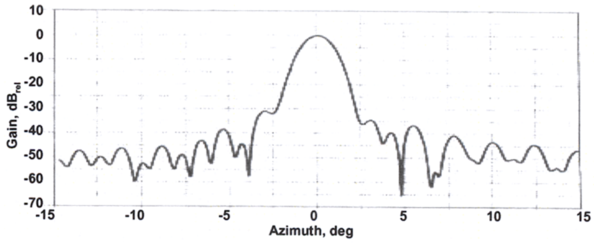

Figure 6: Measured normalised antenna pattern (one-way) for a modern ATC antenna.

6.1.2 Elevation sensitivity

ATC radars are not required to resolve targets in elevation, therefore they typically have a broad elevation sensitivity pattern, matched to their required height coverage. Targets are reported in 2-dimensions (2D - range and azimuth). Windfarm clutter and desensitisation effects can thus have an impact at all elevations, Figure 7.

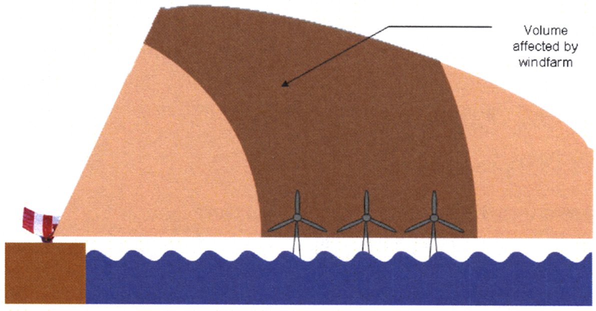

Figure 7: Schematic of affected volume of 2D radar

AD radars are required to resolve and report targets in 3-dimensions (3D - range, azimuth and elevation) and typically employ elevation phased arrays to generate multiple beams, Figure 8. Low elevation beams can illuminate windfarms; radar performance for low flying targets will thus be affected by clutter and desensitisation. In the case of scanning beam radar, higher elevation beams should be largely unaffected except for elevation sidelobe effects similar to the azimuth sidelobe effects described above. Radar using a single broad transmit beam and stacked receive beams will not benefit from two-way sidelobe reductions and are thus more likely to suffer effects in their higher elevation beams too.

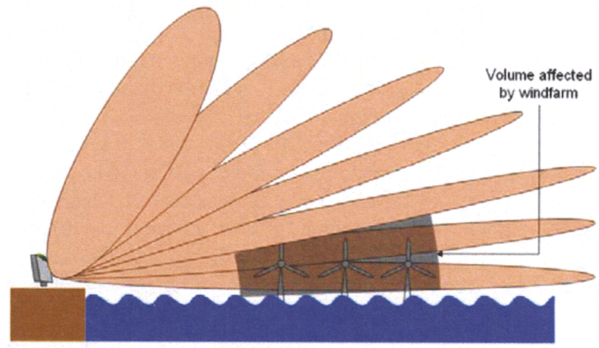

Figure 8: Schematic of affected volume of a 3D scanning beam radar

6.2 Primary RF receiver front end

Amplifier components in the receiver front end of a radar exposed to excessively large received signals of large wind turbine returns can become saturated or limited. In the case of saturation, a period of time may be required to recover and would effectively desensitise the radar over an extended range. This would require very large signal returns and would be unlikely to occur unless wind turbines were particularly large and close to the radar.

In the case of limiting, in a short pulse system this would not have a significant effect, however, in long pulse compression systems, these components are upstream of the pulse compression processing and can cause increased pulse compression sidelobes and small signal suppression of wanted target echoes overlapped in time with the turbine targets.

These saturation and limiting effects can thus cause loss of sensitivity to smaller wanted targets over ranges that extend out to approximately an uncompressed pulse length from the turbines. For modern pulse compression systems, with pulse lengths of 100µs and more, this could lead to desensitisation out to many kilometres in range from a windfarm.

6.3 Signal processor

There are three areas in a radar signal processor where large windfarm returns can have a negative effect:

6.3.1 Analogue to Digital Converter (ADC)

ADCs used in radar systems sample incoming signals using a certain number of bits of resolution; this determines the dynamic range of the converter. Incoming signals that exceed the dynamic range of the ADC will not be represented properly and limiting effects similar to those caused by amplifier components (degradation of pulse compression sidelobes and small signal suppression) may occur as a result. Typically ADCs in a radar system are more likely to exceed their dynamic range than amplifier components and thus potentially cause desensitisation of the radar.

6.3.2 Pulse compression processing

Many older radar systems use either Magnetron or Travelling Wave Tube (TWT) high power transmitter devices. These typically transmit relatively short pulses at very high power in order to illuminate targets with sufficient energy to allow detection of the reflected echoes. Range resolution is achieved by using very short pulses, which typically do not have significant range sidelobes.

As a result of the adoption of solid state transmitter technology in later generations of radar systems, the peak transmitted power of these systems has reduced. In order to illuminate targets with sufficient energy to meet detection requirements, longer pulses are used. Range resolution is maintained by frequency modulating these transmitted pulses and applying pulse compression processing on the received signals.

However, as a consequence of pulse compression processing, target energy can appear in the radar at extended ranges either side of the true target range ($\pm\frac{1}{2}c\tau_u$, where c = speed of light and τ_u = uncompressed pulse length). These range processing sidelobes are smaller than the main range processing peak. Figure 9 illustrates the theoretical range sidelobe performance of an example 100µs modulated pulse from a modern ATC radar. In practice range sidelobe performance is likely to be worse than these plots indicate.

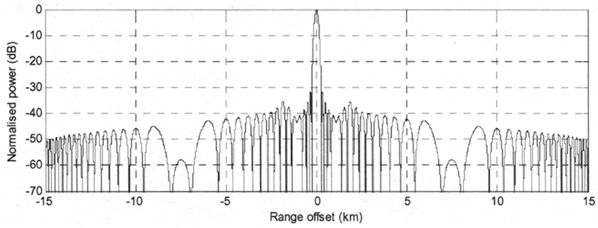

Figure 9: Pulse compression range sidelobe performance

These sidelobes roll off to approx. -50dB smaller than the peak, however, as discussed above, since approx. -70dB is required to avoid impacting significantly on the radar performance, these sidelobe levels may not be small enough and wind turbines may cause desensitisation to small wanted targets via these sidelobes or even be themselves detected. In the example in Figure 9 they exist out to approx. ±15km.

Short pulse systems, which do not suffer significant sidelobe effects, should be largely unaffected in this way over extended ranges from the windfarms.

6.3.3 Doppler clutter processing

Doppler processing, in the form of Moving Target Indication (MTI) or Moving Target Discrimination (MTD) are techniques used by radar to discriminate moving wanted target returns from stationary or slow moving clutter returns. As indicated in Table 1, wind turbine blades can have tip velocities up to 79m/s and have a large variation of velocities along them from root to tip. These high tip speeds are similar to those of slow moving wanted air targets such as general aviation traffic, helicopters and commercial transport jets coming in to land. In addition, since the Pulse Repetition Frequency (PRF) of surveillance radar systems are typically relatively low, their Doppler velocity ambiguities are much smaller than these speeds and even using techniques such as MTI or MTD it is not possible to discriminate wind turbine returns from moving wanted targets. In these cases, many unwanted turbine returns can be reported ([12], [13], [14]).

6.3.4 Constant False Alarm Rate (CFAR) processing

CFAR processing is employed in the signal processing of nearly all modern radar systems. It typically consists of at least a background averager and sometimes clutter maps. These techniques are used selectively in radar designs so that not all processing channels will incorporate all of these features. The descriptions below explain typical actions of these features but details will differ significantly between radar designs.

6.3.5 Background averager

The purpose of a background averager is to estimate the local noise and clutter level in the vicinity of a given candidate target range cell. This is achieved by calculating rolling averages over a number of range cells either side of each candidate target range cell. This average is used to calculate a target detection threshold level. The larger the average, the higher the threshold and the less sensitive the radar is to small targets. An example background averager design is illustrated in Figure 10.

If a particularly large return, such as a wind turbine, is included in the background average calculation it will cause the background average level to be higher than in the absence of the turbine. This in turn will act to desensitise the radar. Since the background averager uses values from a number of range cells either side of a particular target cell, the effect of a large wind turbine can extend up to many kilometres away from a turbine.

In addition, range sidelobe returns from wind turbines will also contribute to increased background average values and this effect will occur over all ranges where the range sidelobes are present (also many kilometres outside of a windfarm). This effect, however, will not be so large and may only affect already marginal detections.

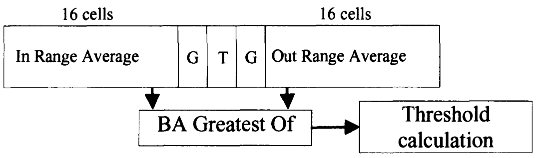

Figure 10: Example Background Averager design

6.3.6 Clutter mapping

In some radar systems clutter maps are also maintained. Many of the desensitisation effects observed in AD radar trials ([12], [14]) are a result of the radar's clutter map implementation [11]. In this case two clutter maps were maintained; a Ground map with large clutter cells containing the maximum return from a number of range cells over several azimuth beamwidths of the lowest beam and a similar Aloft map of returns from the remaining elevation beams. Detection thresholds were calculated based on clutter cell values.

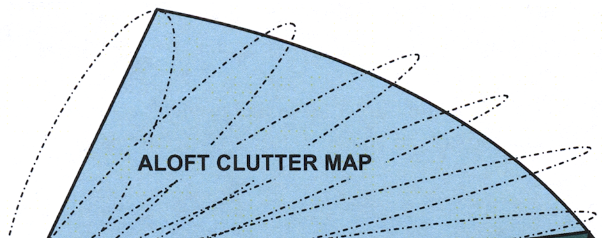

Figure 11: Clutter map partitioning in the trials AD radar [11]

This design was originally optimised for distributed clutter such as ground or weather. With large point ground clutter such as wind turbines, an entire clutter cell was affected and the radar thus desensitised over a correspondingly large volume. Additionally, sidelobe turbine returns in the second beam contributed to the aloft clutter map and caused desensitisation to high altitude wanted targets.

6.4 Data processor / tracker

The predicted and observed effects of windfarms on radar serve to desensitise the radar so that wanted targets are no longer detected, while at the same time increasing the numbers of unwanted returns.

Under these conditions a scan-to-scan plot tracker has very little useful information to operate on. This results in the observed reduction in tracking performance in the vicinity of a windfarm. In particular, two effects can occur:

6.4.1 Initiation of unwanted tracks

With the large number of unwanted wind turbine plots presented to the tracker, a large number of tracks will be formed, particularly since turbines are normally sufficiently closely spaced in windfarms to fall within tracker association ranges of each other. This can lead to overload of the tracker processor if too many of these false tracks are generated.

6.4.2 Track seduction

If detections of wanted targets reduce while the number of unwanted returns in a windfarm increases; an existing wanted target track may become associated with unwanted returns in the vicinity of the windfarm. This process, known as 'Track seduction' means the radar is no longer tracking the correct target. Once the real target leaves the vicinity of the windfarm, the tracker must re-initialise a new track on it.

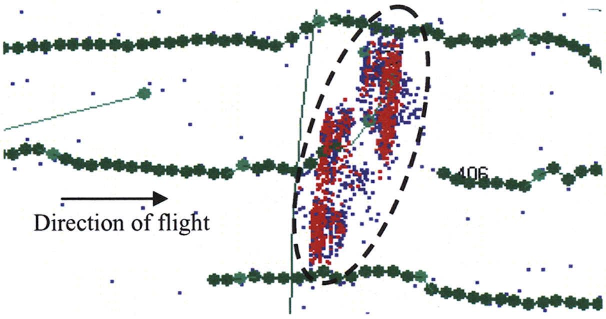

Figure 12: Recorded tracker time history [13], note the number of turbine plots (circled) and the seduction and loss of the (green) aircraft track in the windfarm with subsequent re-initialisation afterwards

7 Conclusions

It is clear that, as a result of their large RCS and the range and magnitude of the velocity of their moving blades, wind turbines present a very challenging environment for surveillance radars to operate in. As described in this paper, many of the components and designs of these radars are susceptible to windfarm returns and result in many of the observed effects, including:

- Clutter: Increased number of unwanted returns reported in the area of windfarms due to the detection of wind turbine echoes.
- Desensitisation: Reduced probability of detection for wanted air targets in a region extending above and around windfarms in both range and azimuth.
- Consequent loss of wanted target plotting and tracking performance in the affected areas

These effects result in a number of operational issues for both ATC service providers and Air Defence radar operators in fulfilling their missions in the vicinity of windfarms and have resulted in well publicised objections to windfarm projects by various radar stakeholders ([15],[16],[17],[18]). In 2007 it was estimated that up to 80% of UK windfarm developments were halted due to radar objections [19].

In order to meet government renewable energy targets, while maintaining air safety and air defence in the UK, it is imperative that mitigation options are found to allow windfarms and radars to co-exist. A detailed knowledge of the causes of windfarm effects on radars, is key to that process.

A description of a number of mitigation options, conceived and investigated by BAE Systems is the subject of a follow on paper entitled 'Options for Mitigation of the Effects of Windfarms on Radar Systems' [20].

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Glossary

AD	Air Defence
ATC	Air Traffic Control
BWEA	British Wind Energy Association
CFAR	Constant False Alarm Rate
DTI	Department of Trade and Industry
MOD	Ministry of Defence (UK)
MTI	Moving Target Indication
MTD	Moving Target Discrimination
RCS	Radar Cross Section
RF	Radio Frequency

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