WINDFARM CHARACTERISTICS AND THEIR EFFECT ON RADAR SYSTEMS

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Keywords: Radar, Wind, Windfarm, Power, Aviation.

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, 15% by 2015 and 20% by 2020. 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 ATC and Air Defence radar. This paper explores the effects on radar system components, of the echo signals received as a result of illuminating 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

The first wind farm in the UK was built at Delabole in Cornwall and became operational with 10 400kW turbines in November 1993. Since then windfarm deployment has spread across the UK both on and offshore with a total of 133 operational windfarms and a total capacity of close to 2GW. A further 27 are under construction, 91 are consented and 210 are in planning. Should all of these become operational they would have a combined capacity of 15GW. Figure 1 is an up to date map of their locations.

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.

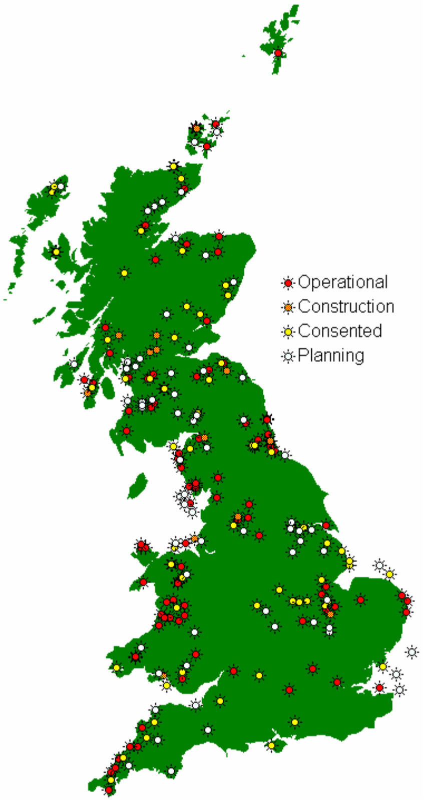

Figure 1 Map of windfarm disposition in the UK

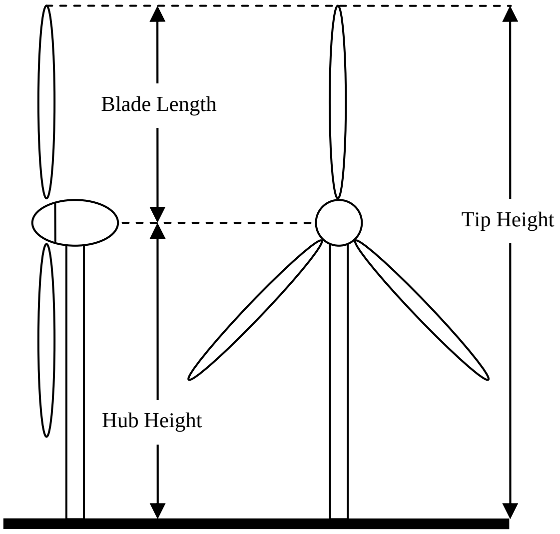

Figure 2 Physical configuration of a typical wind turbine

Turbine rating	3MW	4.5MW	6MW
Blade Length (m)	45 - 50	50 - 60	60 - 70
Hub height (m)	70 – 80	80 - 90	90 - 110
Tip height (m)	115 – 130	130 - 150	150 – 180
Rotation rate (rpm)	16	14	12
Max Tip speed (m/s)	84	100	120

Table 1: Typical wind turbine parameters

Electromagnetic modelling in the S-band (2.7 - 2.9GHz) and the L-band (~1.3GHz) operating ranges 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 500 000m^2 (57dBm^2). This is composed of approximately 400 000m^2 (56dBm^2) peak for the tower and 35 000m^2 (45dBm^2) peak for each blade.

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 constantly 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 commercial transport jets may have an average RCS of only around 100m^2 (20dBm^2). Of particular importance is the velocity of the moving blades, at certain orientations this will approach the maximum tip speeds, which 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.

4 Affected radar

The radar most affected by windfarm interactions are typically of the long range surveillance type, since they operate over extended ranges. These include both 2D en-route and terminal manoeuvring area ATC radar and 3D Air Defence (AD) radar. In the UK ATC radar are typically situated at or near to airfields, although a number of en-route radar are sited in other locations, such as hill tops, to provide good long range cover. Air Defence radar are typically sited near to the coast.

5 Radar stakeholder concerns

{Background on NATS, Airports and UK MOD concerns.}

In order to investigate these concerns a number of radar / windfarm trials have been conducted over several years, these have included both 2D ATC and 3D AD radar sensors. These trials investigated the effect of operational windfarms on radar performance. Observed effects included:

- Increased number of unwanted returns (false alarms) reported in the area of the windfarm due to the detection of wind turbine echoes - Clutter.
- Reduced probability of detection for wanted air targets in a region extending above and around the windfarm in both range and azimuth - Desensitisation.
- Consequent loss of wanted target plot and track integrity in the affected areas

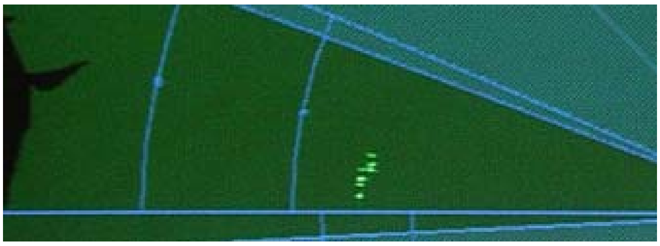

Figure 3 Example of some observed windfarm clutter

6 Impact on radar systems

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

Figure 4 is a block diagram of a typical surveillance radar system design; Table 2 outlines the functions of the various sub-systems.

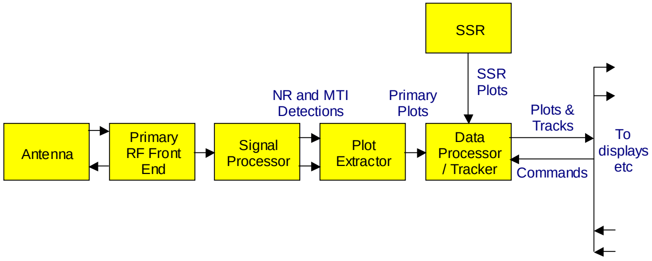

Figure 4 Radar system block diagram

Antenna	Either shaped reflector or phased array
Primary RF Front End	Transmitter(s), Receiver(s), Duplexer etc.
Signal Processor	Extracts useful signal information about wanted targets whilst rejecting undesired signals (such as clutter). Normally implemented digitally, this function usually comprises Analogue to Digital Conversion, Pulse Compression, Integration Processing, Clutter Filtering, CFAR and 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 the 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

While a radar is most sensitive in the antenna boresight direction, an unavoidable feature of antenna designs are sidelobes where the radar is sensitive (although at a much lower level) to returns arriving from off boresight directions. A typical one-way azimuth pattern is illustrated in Figure 5.

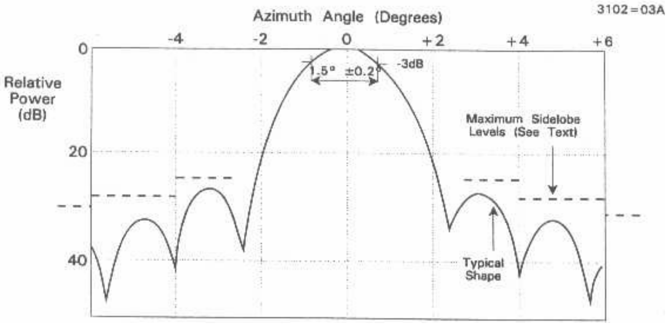

Figure 5 Typical one-way antenna sensitivity pattern for an ATC antenna

Since wind turbines present such large targets they may still be detected by the radar via these sidelobes and be reported on the display. In order to avoid this occurring, the two-way sidelobe level must be very small (~-70dB). Two-way sidelobes are calculated by doubling the one-way levels; examination of Figure 5 reveals that the azimuth angle required to achieve -70dB two way (-35dB one-way) sidelobes is approximately 6° either side of the beam peak.

{NOTE - will add a discussion on the fact that 2D radar cannot discriminate in elevation so are affected at all heights above a windfarm and a discussion on elevation sidelobes for 3D radar}

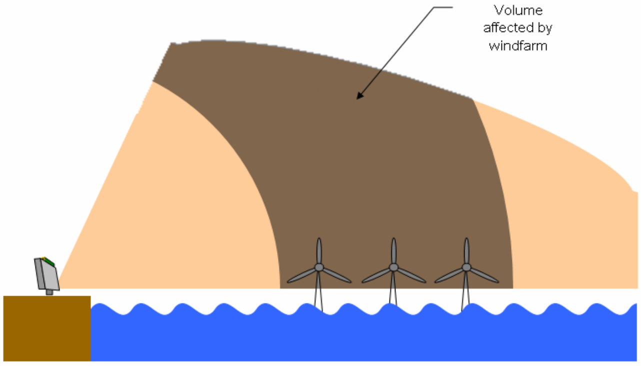

Figure 6 Typical Cosecant squared surveillance volume of 2D radar

6.2 Primary RF front end

Amplifier components in the receiver front end of a radar may be exposed to excessively large input signals such as might be expected from large wind turbine returns. This can lead to saturation and/or limiting. While Low Noise Amplifier (LNA) components are protected from damage by protector circuits, they are still capable of being driven into saturation. A period of time may therefore be required for the components to recover back to their linear amplification range. This would effectively desensitise the radar over an extended range. Such an occurrence, however, would require very large signal returns and would be unlikely to occur unless wind turbines were particularly close to the radar.

Intermediate Frequency (IF) units, downstream of the LNAs in the RF front end, typically use limiting amplifiers. Such amplifiers have their outputs limited to a specified maximum. 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 the received echoes are still in their long pulse uncompressed form. In systems such as these, when pre-compression limiting occurs this 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 half an uncompressed pulse length from the turbines. For modern pulse compression systems, with pulse lengths of 100μs and more, this can lead to desensitisation out to many km 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:

The Analogue to Digital Converter (ADC)

The Analogue to Digital Converters used in radar systems sample incoming signals using a certain number of bits of resolution - which determines the dynamic range of the converter. Incoming signals which 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. In fact, the ADCs in a radar system are more likely to exceed their dynamic range that amplifier components and thus potentially cause desensitisation of the radar.

Pulse compression processing

Many older civil 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 don't have significant range sidelobes.

As a result of the adoption of solid state transmitter technology in later generations of radar systems, the peak transmitted pulse 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 in the radar, target energy can appear at extended ranges either side of the true target range, these range processing sidelobes are smaller than the main range processing peak. Figure 7 illustrates the theoretical range sidelobe performance of an example 100μs modulated pulse from a modern ATC radar. In practice range sidelobe performance of the systems is likely to be worse than these plots indicate.

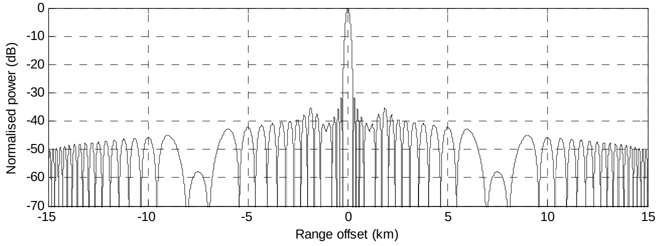

Figure 7 Pulse compression range sidelobe performance

These sidelobes roll off to approx. -50dB smaller than the peak, however, since approx. -70dB is required to avoid impacting significantly on the radar performance, these sidelobe levels are not small enough and wind turbines may be detected by the radar via these sidelobes and be reported on the display or cause the radar to be less sensitive to small wanted targets. The extent of the range sidelobes depends on the radar transmitted pulse length. In the example in Figure 7 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.

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 120m/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 commercial transport jets coming in to land, general aviation traffic and helicopters. In addition, since the Pulse Repetition Frequency (PRF) of surveillance radar 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 fast moving wanted targets. In these cases, many unwanted turbine returns (false alarms / clutter plots) are reported.

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.

Background averager

The purpose of the 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 8.

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, large 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 kilometers outside of a windfarm). This effect, however, will not be so large and may only affect already marginal detections.

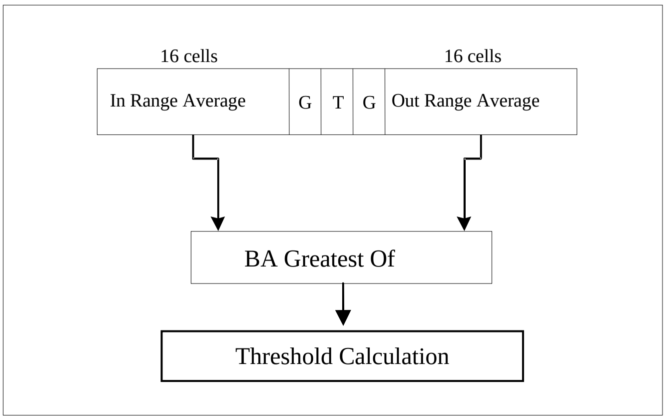

Figure 8 Example Background Averager design

Clutter map

In some radar systems clutter maps are also maintained; these record the location of large clutter returns and contribute to the calculation of detection thresholds. However, the clutter map processing is typically optimised to distributed clutter such as ground and weather clutter rather than very large point clutter such as wind turbines. This can lead to radar desensitisation over large areas in the vicinity of wind turbines.

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 unwanted return (false alarm) rate.

Under these conditions a simple tracker has very little useful information to operate on. This results in the observed reduction in track integrity in the vicinity of a windfarm. In particular, two effects can occur:

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 radar tracker association ranges of each other. This can lead to overload of the tracker processor if too many of these false tracks are generated.

Track seduction

If detections of wanted targets reduce while the number of unwanted returns in a windfarm increases; an existing 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.

Conclusions

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

- Increased number of unwanted returns (false alarms) reported in the area of the windfarm due to the detection of wind turbine echoes - Clutter.
- Reduced probability of detection for wanted air targets in a region extending above and around the windfarm in both range and azimuth - Desensitisation.
- Consequent loss of wanted target plot and track integrity 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 in the UK and abroad.

A detailed knowledge of the causes of these windfarm effects on radar, however, is key to the process of designing mitigation options to reduce or remove them.

A detailed description of a number of mitigation options, investigated by BAE Systems Insyte is the subject of the follow on paper entitled ‘OPTIONS FOR MITIGATION OF THE EFFECTS OF WINDFARMS ON RADAR SYTEMS’

Acknowledgements

BAES Insyte WF team
DTI
UK MOD
BWEA
{Will provide more detailed acknowledgements here}

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