# OPTIONS FOR MITIGATION OF THE EFFECTS OF WINDFARMS ON RADAR SYTEMS

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## Abstract

This paper follows on from a previous paper 'Windfarm characteristics and their effect on radar systems' [1] and considers various options for the mitigation of these previously described windfarm effects. Options include terrain screening, modifications/upgrades to existing radar, new radar designs, data fusion schemes utilising data from multiple sensors, stealthy wind turbines and windfarm layout.

## 1 Introduction

In general, the effect of windfarms within radio line of sight of a radar (without any mitigation measures) is to reduce the performance of the radar in the vicinity of the windfarms in the following ways:

- 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 are the result of various physical and radar systems properties, as described in [1]; they are generally limited to the locale of windfarms or the immediate vicinity within a few kilometres. Depending on the detailed design of the radar, some effects may also be expected at extended ranges or azimuths either side the windfarm.

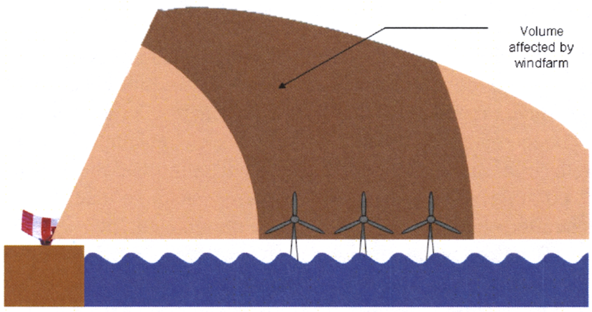



Figure 1: Schematic of a windfarm affected zone

The following sections outline various options for mitigating these effects or at the least reducing the size of affected areas.

## 2 Terrain screening

The most straightforward method of avoiding the impact of windfarms on radar systems is to ensure that radar systems do not illuminate windfarms with sufficient energy to affect the radar's performance; this can be achieved using terrain screening.

Terrain can provide a very effective obstacle to radio propagation. Figure 2 is the output of a radio propagation modelling tool utilising a terrain database. The coloured areas of the map indicate areas where turbines of a given height and RCS would be illuminated with sufficient energy by the radar at RAF Waddington to have an impact on its performance.

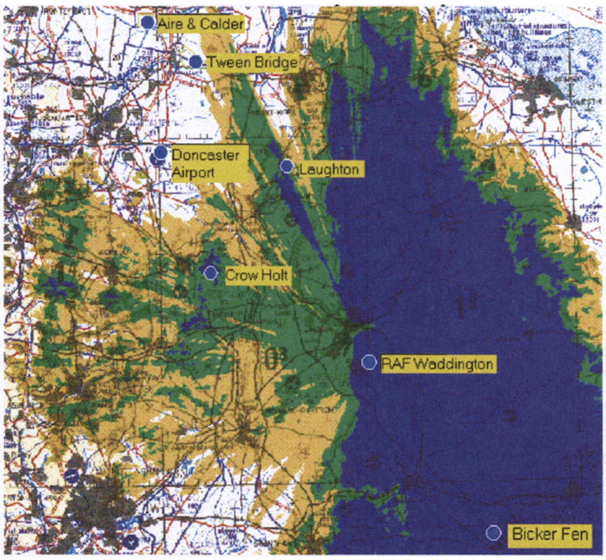



Figure 2: Radar coverage of windfarms from RAF Waddington [2] annotated with windfarm locations.

It can be seen that Bicker Fen, Crow Holt and Loughton windfarms would have an impact on RAF Waddington's radar performance, while Aire & Calder and Tween Bridge are sufficiently screened by terrain so as not to have an impact.

This is a particularly useful tool for windfarm developers wanting to know if their proposed sites might attract objections from radar stakeholders. In some cases a developer has considered re-arranging a windfarm design or reducing the height of some turbines in order to forestall any radar objections. In this way mitigation can be achieved at a very early stage.

## 3 Single sensor mitigation options

In cases where a windfarm proposal is within line of sight of an existing radar, there are a number of options for mitigation of the effects within the radar sensor itself.

As per the discussion in [1], the mitigation options considered for single sensors are presented in the context of a typical radar system architecture as illustrated in Figure 3.

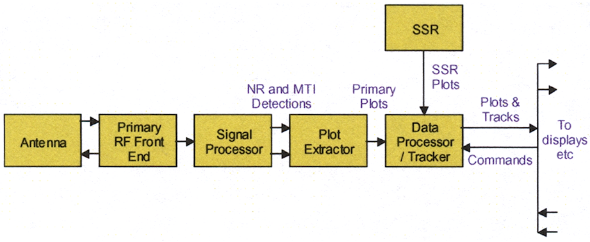



Figure 3: Typical radar system block diagram

The first observation in this section is that complete mitigation is unlikely to be possible for a single sensor since wind turbines have considerably larger RCS than typical wanted targets. Any wanted targets occupying the same range-azimuth (and elevation in 3D radar) resolution cell as a wind turbine will be indistinguishable from the turbine. However, there are options available to reduce the volume over which windfarms do impact on radar performance and optimally approach the minimum volume of a single range-azimuth-elevation cell.

### 3.1 Antenna

#### 3.1.1 Antenna tilt

If suitable terrain is not available to screen a windfarm, it is possible to use antenna tilt to reduce the illumination of a windfarm to a sufficiently low level to avoid a negative impact. In 2D Air Traffic Control (ATC) radar this can be achieved by physically adjusting the tilt of the antenna and/or its feed horns. This is a task normally carried out during commissioning but could be done at a later date if necessary. The main drawback of this approach is that if wind turbine Radar Cross Section (RCS) is very large then a large tilt will be necessary, which may unacceptably reduce detection performance against low altitude wanted aircraft targets at long range - over the entire 360° rotation of the antenna.

#### 3.1.2 Beam switching

In order to achieve detection of low elevation targets at long range and high elevation targets at short range many 2D ATC use two beams, as illustrated in Figure 4, and switch between them at a predetermined range, $R_S$.

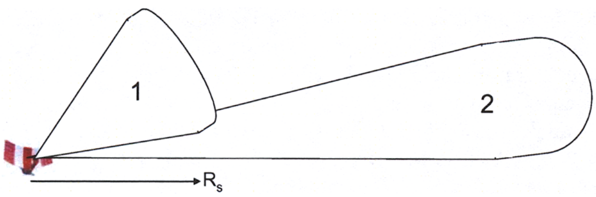



Figure 4: Schematic of a 2D radar twin beam approach.

It has been proposed ([3], [4]) that the reduced sensitivity of the short range beam (1) at low elevations can be exploited by extending the switchover range, $R_S$, beyond the windfarm and thus reducing its probability of detection, while maintaining long range detection of wanted low elevation aircraft targets in the long range beam (2). In software controlled radar the beam switching range could be varied with azimuth, thereby maintaining normal detection performance over the rest of the search volume. The main drawbacks of this beam switching technique is that it may not sufficiently mitigate large RCS turbines and, due to the reduced sensitivity of the short range beam, the probability of detection of wanted aircraft targets will be reduced towards $R_S$ if a windfarm is too far away.

#### 3.1.3 Electronic tilt

3D AD radar, utilising elevation phased arrays (Figure 8 in [1]) are usually capable of electronic tilt (E-tilt) whereby their beams can be tilted by adaptively adjusting phase shifter settings across the array [5]. This E-tilt adjustment can be applied to limited sectors of azimuth, thereby maintaining low level detection performance over the rest of the search volume. This technique was demonstrated during AD radar trials supported by BAE Systems ([5], [6]). While long range, low level detection performance is maintained over the majority of the radar's cover, it is affected in the direction of any windfarms where E-tilt is applied.

#### 3.1.4 Elevation sidelobe control

Another benefit of elevation phased arrays is the possibility of sidelobe suppression/control. With appropriate selection of phase (and possibly amplitude) weighting across an array, the low elevation sidelobe levels of elevation beams can be reduced [7]. This would likely be at the cost of increased sidelobes at higher elevations, which would normally be undesirable. However, in the presence of windfarms this compromise might be acceptable.

### 3.2 Signal Processor Unit (SPU)

There are several key areas of signal processing which may be improved with respect to windfarm mitigation.

#### 3.2.1 Waveform design

As discussed in [1], while minimising range sidelobes is good practice, the range sidelobes of large RCS turbines may still be sufficient to cause extra clutter or desensitise a radar. Since the extent of range sidelobes depends on transmitted pulse length, minimising this pulse length will minimise the extent of possible desensitisation. Systems using magnetron transmitters necessarily use short, unmodulated, pulses and will not suffer range sidelobe effects. Newer systems using TWT or solid state transmitters typically utilise a mix of long modulated pulses for long range detection and shorter modulated or very short unmodulated pulses for short range detection. In ATC systems these are usually split between the long and short range beams respectively, illustrated in Figure

4. AD systems typically use the same beam structure as for long range.
The lack of sidelobes for short range pulses can be exploited by extending the short-to-long switch over range to beyond a windfarm and thereby limiting any wind turbine effects to only the range cells they fall into. In this respect solid state transmitter systems (particularly ATC systems using a short range low gain beam) will be at a disadvantage since they are less capable of generating sufficient peak power to detect small wanted targets at longer ranges using short pulses. This mitigation option does not eliminate windfarm clutter but does prevent desensitisation over extended ranges.

### 3.2.2 Edited background averaging

Large wind turbine returns falling within the rolling window of a background averager can skew the background noise estimates and lead to high detection thresholds. In order to mitigate this effect, large wind turbine returns may be excluded from the background average calculation. These returns can be found using a sorting technique and choosing extreme values or by maintaining a history of range cells containing consistently large returns [5]. This mitigation would not eliminate windfarm clutter but could reduce desensitisation over extended ranges. It would be more effective with short pulses than long pulses where range sidelobes would not be eliminated and could continue to contribute to the background average.

### 3.2.3 High resolution clutter maps

As discussed in [1], large clutter map cells can cause radar desensitisation over large volumes if wind turbine returns fall within them. The most effective mitigation of this effect is to use High Resolution Clutter Maps (HRCM) [5] where the clutter cell size is significantly reduced, thus minimising the volume of desensitised cover.
In addition, by implementing separate HRCM in each of the multiple elevation beams of AD radar, desensitisation over extended elevations can be avoided. This multiple HRCM mitigation option could eliminate consistent wind turbine clutter and approach the minimum volume for desensitisation effects.
Both Edited background averaging techniques and multiple HRCM are being developed for the latest generation BAE Systems Insyte Air Defence radars.

### 3.3 Tracker/Data processor

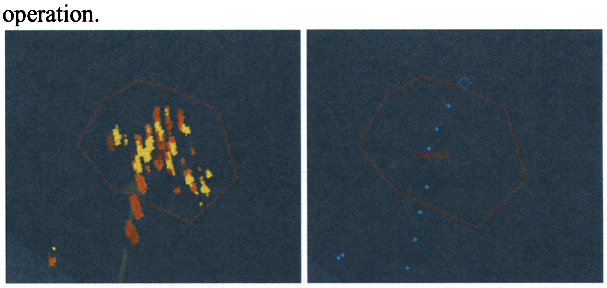
There are several options available to mitigate windfarms using surveillance tracker technology. In general, because trackers are downstream of the radar detection processing, such options are most useful for mitigating clutter and tracker effects and do not deal with desensitisation.

### 3.3.1 Non Automatic Initiation Zones (NAIZ)

Most existing surveillance radar trackers have the option of setting up NAIZ. If applied around an area of windfarm clutter a NAIZ will prevent the initiation of new tracks from within the windfarm thus protecting against tracker overload. NAIZ are limited in that they cannot prevent the display of clutter or track seduction of aircraft flying over a windfarm.

### 3.3.2 Plot / Track filtering

Filtering algorithms may be applied to incoming plot streams and candidate tracks ([8], [9]). Persistent wind turbine plots in particular may be ignored and so not displayed or used in track forming or maintenance of existing aircraft tracks. In the case of wind turbines the characteristics of plots and candidate tracks in particular can be exploited to optimise the filtering process.
This sort of technology has been used successfully in naval surveillance radar trackers to help deal with the challenging naval clutter environment for many years [2]. The BAE Systems Advanced Digital Tracker (ADT) is an example of this technology and is being developed with windfarm mitigation as an objective. In conjunction with the British Wind Energy Association (BWEA), the Department of Trade and Industry (DTI) and the Royal Air Force (RAF), the ADT has been extensively trialled and demonstrated at several radar sites with visibility of a number of windfarms ([2], [10], [11] & [12]). These have included flight trials with a variety of aircraft of varying RCS and flight paths over windfarms. The results of these trials and demonstrations have been very satisfactory and shown significantly reduced levels of unwanted returns and improved target track performance in the vicinity of windfarms compared to non-ADT augmented operation.



(a) (b)

Figure 5: Radar windfarm clutter (a) before and (b) after plot / track filtering with ADT. Note the maintenance of the aircraft track through the windfarm, compared to previous examples (see Figure 12 in [1])

Similar techniques have also been proposed by other manufacturers ([4], [13]).
Such plot / track filtering options do not in themselves improve detection performance on small targets above windfarms. However, if simple changes to SPU detection threshold control logic were made to allow improved target detection (at the cost of increased false alarm rate) extra false alarms could be removed by plot / track filtering while leaving genuine wanted target detections to be displayed and tracked.
Plot/track filtering options also have the benefit that they could be an 'add-on' to affected radar systems with very few, if any, intrusive modifications required.

## 4 Multi sensor mitigation options

An alternative to single sensor mitigation is the use of multiple sensors to provide the required airspace coverage. In its simplest implementation a second, 'Fill-in' radar can be used, provided that it is positioned such that the windfarm in question is not illuminated and it thus suffers no performance degradation, as illustrated in Figure 6. Such a fill-in sensor may be an existing radar or a new radar installation on a site carefully selected to ensure adequate terrain screening.

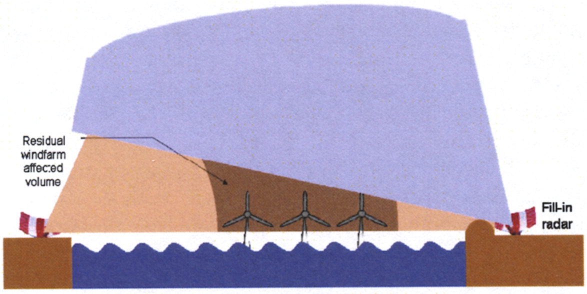
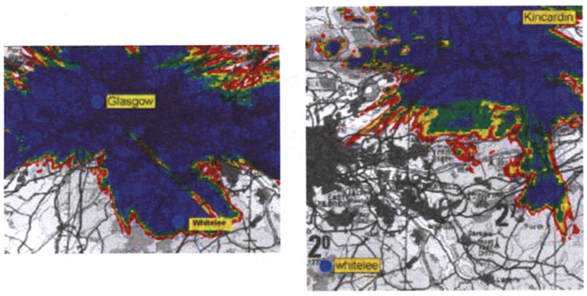



Figure 6: Schematic Fill in radar cover.

The challenge in these cases is to find a suitable location for the fill-in sensor. In the first instance this can be searched for using propagation modelling tools with a terrain database. Figure 7(a) indicates that the Whitelee windfarm in Scotland would be visible to the Glasgow airport radar and cause performance degradation while (b) indicates that Kincardine may provide a suitable fill-in sensor location since it does not have visibility of the windfarm. Further analysis indicates that Kincardine would have visibility of aircraft targets down to approximately 2200ft, which is an operationally useful altitude.




(a) (b)

Figure 7: Whitelee windfarm visibility from (a) Glasgow airport radar (b) Kincardine fill-in location

### 4.1 Data Fusion

Once a suitable fill-in radar site is identified, it will be necessary to provide a data feed from the fill-in and fuse incoming fill-in data with data from the original radar, see Figure 8.

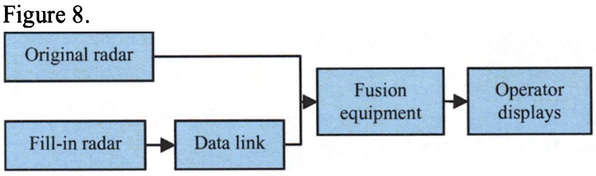



Figure 8: Data fusion architecture

The term 'Data fusion' can encompass a wide range of complex techniques, often for fusing data from disparate sensor types. In the context of windfarm mitigation, using two similar sensors, the simplest form of fusion is to simply replace plot data from the original radar with plot data from the fill-in radar in the vicinity of the windfarm. This technique, known as 'Mosaicing', is illustrated in Figure 9.

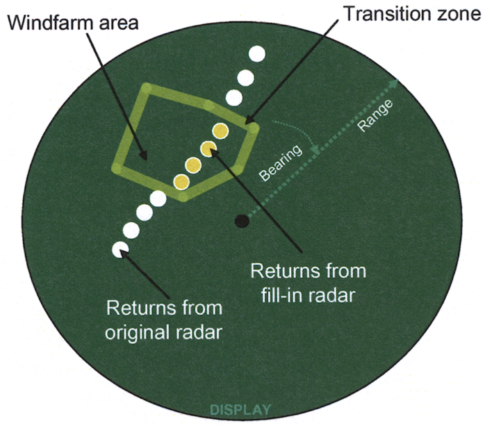



Figure 9: Illustrative mosaiced radar display.

While multi sensor data fusion is potentially a more expensive option, it is perceived, by both radar operational stakeholders and windfarm developers to be the most effective and reliable method of mitigating windfarm effects. Indeed, this very option is being adopted to allow the withdrawal of Glasgow International Airport's objection to the Whitelee windfarm (see section 14 of [14]). Similar proposals are being explored in detail in other civil cases ([15], [16]) and (after being recommended in [5]) is under consideration by the UK MOD as mitigation of proposed windfarms in the Greater Wash area.

## 5 Windfarm / turbine options

The options discussed so far have covered radar based technical mitigation. This section will examine two options available to windfarm developers.

### 5.1 Stealthy wind turbines

As indicated in [1], unmodified wind turbines can have an RCS in excess of $50dBm^2$ and thus present a significant target to a radar. Methods of reducing the RCS of turbines have been an active research area both within BAE Systems ([17], [18]) and other organisations [20] for a number of years (usually funded through the DTI). The focus of BAE Systems effort has been in the accurate electromagnetic modelling of wind turbines (see Figure 10), the identification of appropriate methods and technologies to reduce RCS and, in collaboration with a wind turbine manufacturer [19], the construction and testing of stealthy wind turbine parts. Results have been promising with the best improvements coming from two techniques:

- Shaping of turbine towers and nacelles in order to avoid specular reflections back to a radar

- Integration of Radar Absorbent Material (RAM) into turbine blade sections.

Construction and deployment within line of sight of a radar of two prototype stealthy wind turbines based on this analysis is anticipated within ~18months.

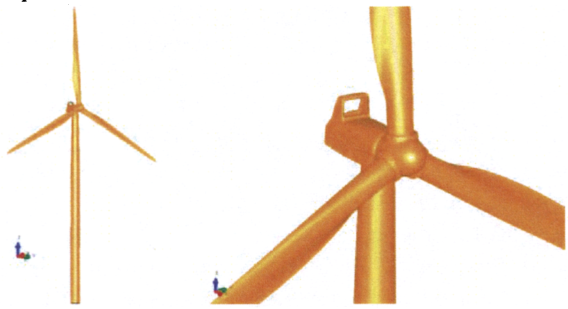


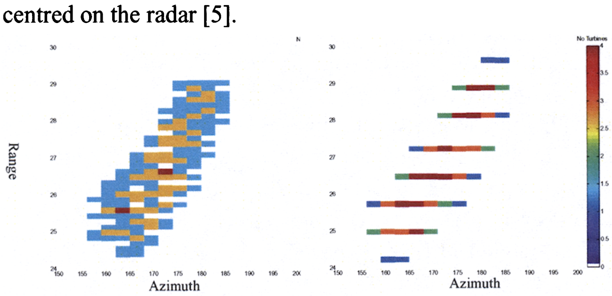
Figure 10: CAD model of a wind turbine used for electromagnetic modelling [18]

Overall, reductions in RCS of around 20dB are expected. While this is not sufficient to completely mitigate windfarm effects on radar, it will significantly improve the effectiveness of other radar based technical mitigation options.

### 5.2 Radar optimised windfarm layout

Windfarms are typically laid out in a grid arrangement, oriented with respect to the prevailing wind direction in order to minimise turbulent wake interactions and maximise energy generation. However this arrangement is rarely optimal for radar operation.

Since (even stealthy) turbines have relatively large RCS, when illuminated by a radar, a turbine will be detected and occupy a Range-Azimuth resolution cell. Any aircraft target in the same resolution cell will not be resolvable from the wind turbine. It is thus desirable to minimise the number of resolution cells occupied by wind turbines. For a given fixed radar location this can be achieved by arranging turbines within the boundaries of the windfarm on circular arcs centred on the radar [5].




(a) (b)

Figure 11: Resolution cell occupancy for a standard ATC radar (a) typical windfarm layout (b) radar optimised layout

Figure 11 indicates, using colour, the number of turbines in a given radar resolution cell vs. range and azimuth. It is clear that, in the typical windfarm layout, many cells are occupied by at least one turbine. In this case ~80% of cells are occupied and thus unavailable for wanted aircraft detections. The optimal layout, using the same number of turbines and the same inter-turbine spacing, however, indicates that while there are more turbines in some cells, there are fewer occupied cells overall (~30%). In this case there are clear range bands where a radar with low range processing sidelobes would be able to achieve inter-turbine target visibility. This is a considerable improvement in available radar coverage.

## 6 Conclusions

It is clear that there are a number of options available to mitigate the effects of windfarm on radar. Although none offer complete mitigation, there are some options and combinations of options which approach this ideal.

Terrain Screening provides useful protection and should be taken into account when selecting the site of a windfarm and is also essential in the selection of a Fill-in radar site.

Some options can be applied to a single affected radar site. In some cases, such as Beam Switching or Plot / Track filtering options this is relatively straightforward. However, in many cases the single sensor techniques would require significant modifications to an existing radar and might be more effectively achieved with the purchase of a new radar with the appropriate enhancements built into the design. This would have an added benefit of extended lifetime over upgrading an existing radar.

Other options require the purchase of an additional radar, to 'Fill-in' areas 'lost' to an original radar, and a data fusion system to combine the data from both radars into a single picture for presentation to an operator. The technology for this option exists today and has already been deemed acceptable mitigation in at least one case [14].

Finally, there are some options that windfarm developers could adopt, which could improve the effectiveness of many of the radar technical mitigation options.

## 7 Acknowledgements

The Author wishes to acknowledge the DTI for it's funding of much of the work involved, numerous engineers and scientists across BAE Systems (in particular within Insyte for their radar expertise and the Advanced Technology Centres for their RCS reduction expertise) as well as the UK MOD and the BWEA for their co-operation in trials exercises.

## 8 Glossary

| | |
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| AD | Air Defence |
| ADT | Advanced Digital Tracker |
| ATC | Air Traffic Control |
| BWEA | British Wind Energy Association |
| CAD | Computer Aided Design |
| CFAR | Constant False Alarm Rate |
| DTI | Department of Trade and Industry |
| HRCM | High Resolution Clutter Map |
| MOD | Ministry of Defence (UK) |
| NAIZ | Non Automatic Initiation Zone |
| RAF | Royal Air Force |

RCS Radar Cross Section
SPU Signal Processor Unit

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