FEASIBILITY OF MITIGATING THE EFFECTS OF WINDFARMS ON PRIMARY RADAR

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EXECUTIVE SUMMARY

Objectives of the Study

The objective of the study was to assess the feasibility of modifying civil and military radars to mitigate the effects from wind turbines, provide costs for implementing changes to the radar and produce text as guidelines for planning wind farms in the vicinity of radars.

Principles of Radar

Fundamentally a simple radar sensor consists of a radio frequency transmitter, a directional antenna and a receiver followed by a processor and a display. The radar transmits a pulse of electromagnetic energy via the antenna in a known direction. Upon reflection from an object, a proportion of the energy is reflected back as a signal to the radar antenna for amplification and signal processing before being displayed as a radar picture. The range to a reflecting object is based on the measured time between the energy leaving the radar and the reflected energy being received.

The received signal at the radar contains reflections from many objects, both moving and stationary. Reflected signals from stationary objects such as trees, the ground and even wind turbine towers are collectively termed clutter. Most modern radars are designed to differentiate between clutter and moving objects based on the Doppler effect, however there are many effects that conspire to reduce performance, including distortion of the received signal. Radars are susceptible to distortion as a consequence of high level signals reflected from highly reflective large objects that exceed the limits of the radar design.

Extent of Wind Turbine Effects on Radar Signals

The wind turbine is perceived as consisting of three major elements, the tower, nacelle and blade assembly. Metal towers reflect a high proportion of the transmitted signal back to the radar. The consequences are:

i) A large reflection can result in amplitude limiting within the receiver or signal processing and therefore induce distortion, possibly resulting in desensitisation and reduced detection of aircraft in the vicinity.

ii) The operator is unaware of desensitisation and missing aircraft responses.

iii) Turbine blades are moving and therefore impose a Doppler effect on the reflected signal. Techniques currently included in most radar processing to distinguish between reflections from moving and stationary objects are unable to differentiate between the Doppler effects imposed by moving turbine blades and Doppler effects imposed by a moving aircraft.

iv) The operator is presented with a confused picture that declares both aircraft and wind turbines as moving objects.

Techniques that “blank” the radar output in the vicinity of turbines represent a loss of detecting air-traffic in an area greater than that occupied by the windfarm and extending up to the maximum altitude of the radar coverage.

Before changes to the radar can be decided it is necessary to understand the effects of wind turbines on the radar. Consequently, as part of the study, the reflection characteristsics of a notional turbine have been estimated to identify which parts of the radar sensor are likely to be affected.

Summary of Results from Modelling the Effect of Wind Turbines

Currently in the UK there are 37 different identifiable designs of wind turbine. Since it is essential that any radar modifications are robust against current and future windfarms, modelling represented a demanding set of turbine characteristics. A survey of key turbine characteristics enabled construction of a model that represents a large, near future, turbine design. A solution based on this model is also considered valid for all current designs.

A mathematical model, generated from the chosen turbine design, established the Radar Cross Section (RCS) for a range of different conditions, illuminating directions and radar frequency bands. Results arising from the modelling activity indicate salient features of the turbine that could be used to develop more "radar friendly" turbine designs.

Civil and military radar installations within the UK have been identified and their non-classified details summarised. **No two radar installations are alike** since the operational settings for the radar are customised to the local requirements, so generating one set of definitive radar parameters to assess performance at all sites is impossible. For this reason a generic set of radar characteristics have been used to establish the effects of wind turbines. **A key outcome of this activity is that a detailed understanding of the designs and features of each "victim" radar will be required to assess the impact of a wind farm proposal.**

There are key aspects of turbine design that can be modified to reduce the radar signature:

- Shape of tower – the surface shapes and angles can be arranged to divert reflected energy away from the direction of the radar.
- Shape and materials of the nacelle – making the nacelle covers from reflective material will shield the complex internal structures. Then shaping covers to divert the reflections will reduce the impact on ground radars.
- Surface treatments – a range of radar absorbent materials are available than can produce some reduction in radar cross section. The effectiveness of these materials is limited but they could be used to overcome specific problems on individual sites.

Treatment of the blades will be limited by the need to maintain aerodynamically efficient shapes and surfaces. In the long term the reflective characteristics the blades may be dictated by the build-up of contaminants, especially salts, on the surfaces.

Costs

The costs of a programme of modifications to the civil ATC radar base in the UK will depend on many factors. Minimising this cost would require a collaborative programme that studies, identifies and proves design solutions in advance of the need to modify any radars. Even given such a programme, it is evident from this study that individual combinations of windfarms and radars will need to be studied to some degree to identify design specific issues.

A set of assumptions has been proposed that identify only 30 of the UK radars would need modification, and that a range of modifications from very simple to very complex will be required. Without identifying the sources of funding ot the allocation of these funds to the various organisations that would be involved the cost of an implementation programme has been estimated. The cost of the site specific elements, the radar modifications and the acceptance process is thought to lie between £8M and £19M at 2003 rates.

Conclusions

During the study it became evident that various effects would be unique to particular ATC and defence radar types. These effects have been classified into two groups:

- Signal distortion within the radar signal processing causing loss of performance.
- Detection of erroneous signals producing output to the radar display

Signal distortion is caused by the very large RCS of wind turbines. Predictions from modelling and reports from radar installations affected by turbines indicate significant variability in the level of distortion between radar sites and across operating conditions. Many radar installations may not suffer degradation at all.

Only a proportion of radars may suffer from wind turbine problems although at present the ratio is unknown. Simply modifying the radar signal processing to blank the detection of turbines is considered unsatisfactory for meeting the overriding requirement to maintain air traffic safety in ATC radars and to meet the more stringent requirements of military radars. Actually the problem is more complex as implied from the effects described above.

Should distortion of signals prove to be a problem, and if no other measures can be found to minimise the effects, then the necessary intrusive modifications to the radar will require detailed knowledge of the system designs and implementation.

Effects from detecting erroneous signals are significantly reduced by adding to the radar non-intrusively, a modern "plot filter" using the latest sophisticated algorithms.

Outside modifying the radar system, a range of other approaches might require investigation during each windfarm planning application:

- Geometric layout and location of the wind farm.
- Changes to the design of the turbines to reduce their "radar signatures"
- Changes to air traffic routes in the vicinity of wind farms
- Changes to the status of the affected airports
- Re-location of the affected radars
- Deployment of additional military radars to “fill in” the areas where coverage has been lost

Solutions to the wind farm problem are variable hence costing the solutions is also variable. To estimate the cost, a statistical range of factors has been considered:

- Support of planning application through to qualification of the modified radar
- Variation of the different modifications
- Trend is for reduced costs as modifications and experience become more mature

Costs have been estimated based on current knowledge of the issues.

Recommendations

Various issues have been identified by this study that warrant future consideration.

- Other systems and equipment that use radar techniques.
- Specialised features of defence radars and the different functions they perform
- Establishing a mathematical turbine model for specifying future radar systems.
- Establishing a pre-emptive programme for radar modifications to minimise delays in granting planning applications for wind farms.

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SECTION 1

INTRODUCTION TO THE STUDY

1.1 Study Contract Scope

A study contract was placed on behalf of the DTI to study the feasibility and cost of modifying land based radars in use in the UK for ATC purposes (both civilian and military). The study excludes secondary radars, weather radars, navigation radars, navigation aids, microwave landing systems, airborne radars, etc.

This study content is described in Appendix A to contract W/14/00623/00/00 (Reference 1), from which the following is an extract:

"The purposes of this study are to:

- Determine the technical feasibility of designing a method of filtering unwanted wind turbine echoes from the radar data without causing any significant reduction in the performance of the radar.
- Propose suitable filtering techniques for each type of radar system.
- Determine the technical and practical factors affecting the feasibility of such filters into the current and proposed civil and military radars in use in the UK. The study will also consider other manufacturers' radars, at a generic level.
- Estimate development, production, installation and commissioning costs of fitting an appropriate wind turbine filter to those radars.
- Produce text suitable for inclusion in the 'UK guidelines for Wind Energy, Defence and Civil Aviation Interests'."

1.2 Work Packages

The study comprises 6 technical work packages, which are summarised as follows:

i) Obtain information from manufacturers and operators of wind turbines including data on dimensions, materials and construction.

ii) Model the turbines to estimate the radar cross sections and Doppler effects.

iii) Obtain technical data on civil and military ATC radars in the UK.

iv) Calculate the effects of wind turbines on the performance of these radars.

v) Select candidate filtering methods and calculate the effectiveness at removing the effects of the wind turbines.

vi) Estimate the costs of fitting these filters to the identified radars.

1.3 Report Structure

This report summarises the results obtained in each of the above work packages and is structured so that each section provides a summary of its topic in a predominantly non-technical manner. Technical details and results are provided in the subsequent Appendices at the end of the report for the technical reader, who is assumed to have some familiarity with radar technologies.

This section of the report defines the problem that has been investigated. Since the study is a closely linked set of work packages, the data produced in each work package has been carefully defined to ensure completeness and continuity. Section 2 therefore defines the boundaries of the problem and gives an overall "model" that links the work packages.

Sections 3 to 8 give the results obtained from each of the technical work packages and Section 9 provides overall conclusions and a summary.

Appendix A gives a brief overview of how radars work and the important interactions with objects in the radar coverage. Appendixes B to G provide the technically detailed results of the work packages. A glossary of terms and abbreviations is given at the end of the report in Appendix I.

1.4 Evidence from Existing Installations

Studies have been conducted in a number of European countries, but there is no evidence yet of any work in the USA (Reference 2).

Earlier studies (References 3, 4 and 5) have looked at some empirical evidence and have identified that there are indeed some problems caused by the proximity of wind farms to ATC radars. Observations of the effects on radars used for defence purposes are of course much harder to determine. Reference 3 indicates that trials conducted by the RAF Signals Engineering Establishment identified degradation of radar performance due to wind turbines. AMS are active in this area but are restricted in the information that can be published. Some public domain information is given in References 6, 7 and 8.

The extent of these problems has not yet been fully quantified, but observations from the references above are:

- Wind turbines can be detected and require the operator to categorise them as non-targets.
- Procedural methods have to be devised at some airports to avoid corruption of the required ATC information.
- Detection, where it occurs, is variable from time to time.
- Angular errors are introduced (only reported for secondary radars).

1.5 Potential Effects for Study

As radar engineers we presume that other effects are also going on that would not be obvious to an operator. Potential effects are:

- Reduction in radar sensitivity causing the loss of aircraft detection in the vicinity of the wind turbine. Magnitude of losses and associated proximity of aircraft to the wind turbine depend on many factors including the size of aircraft, distance between the radar and turbine(s), attitude of the turbine and type of radar.
- Detection of aircraft on an incorrect bearing and range due to reflections from the turbine.
- Detection of the wind turbine that appears as a stationary aircraft, for example a helicopter.

1.6 Issues for Study

The effects of introducing turbines into the environment that surrounds a radar can be treated as separate issues:

- The detection of the turbines by the radar and the effect this has on the information presented to the operator
- The effect that the turbines will have on the detection of desired targets (whether this is degraded in some way)

This study has attempted to quantify these effects as far as is possible within the study constraints.

1.7 Study Approach

To assess the problems that may be caused by wind turbines, the problem space must be treated as a system. In the context of this study the problem space is any given radar and the environment that surrounds it including the presence of one or more wind turbines. The first task is to establish the boundaries of the problem space in physical and temporal terms. The second task is to define the objects in the problem space and the interactions between them.

The interactions between the objects in the problem space are then used to identify the key attributes of all the objects. These attributes allow the mathematical analysis of the effects that are generated by wind turbines. Once these effects are understood then appropriate mitigation techniques are identified and evaluated. Those that appear to be effective are then estimated to give a broad idea of the cost of implementation.

The effects that are considered to be significant then are treated as requirements that should be met by future installations both of turbines and of radars.

Further investigation of the problem and evolution of potential solutions are recommended throughout the study. Military radar and other systems vulnerable to wind turbines are proposed for further study.

1.8 Problem Boundaries

1.8.1 Physical problem space

The physical problem space in this case encompasses the radar, the turbines, the targets that are intended to be detected and objects that are to be rejected because they are not of interest to the ATC radar operator. Part of the problem space is the local environment that encloses the radar and the objects around it. The geometry effects caused by local terrain are discussed below, but do not form part of this study.

In Figure 1.1, the energy from the radar illuminates all the objects surrounding the radar. These objects include things that the operator is not interested in (buildings, hills, trees, waves on the sea surface, etc) as well as the things he wishes to see (aircraft). The energy reflected from all these objects is received by the radar, is then processed and displayed to the operator who interprets the information.

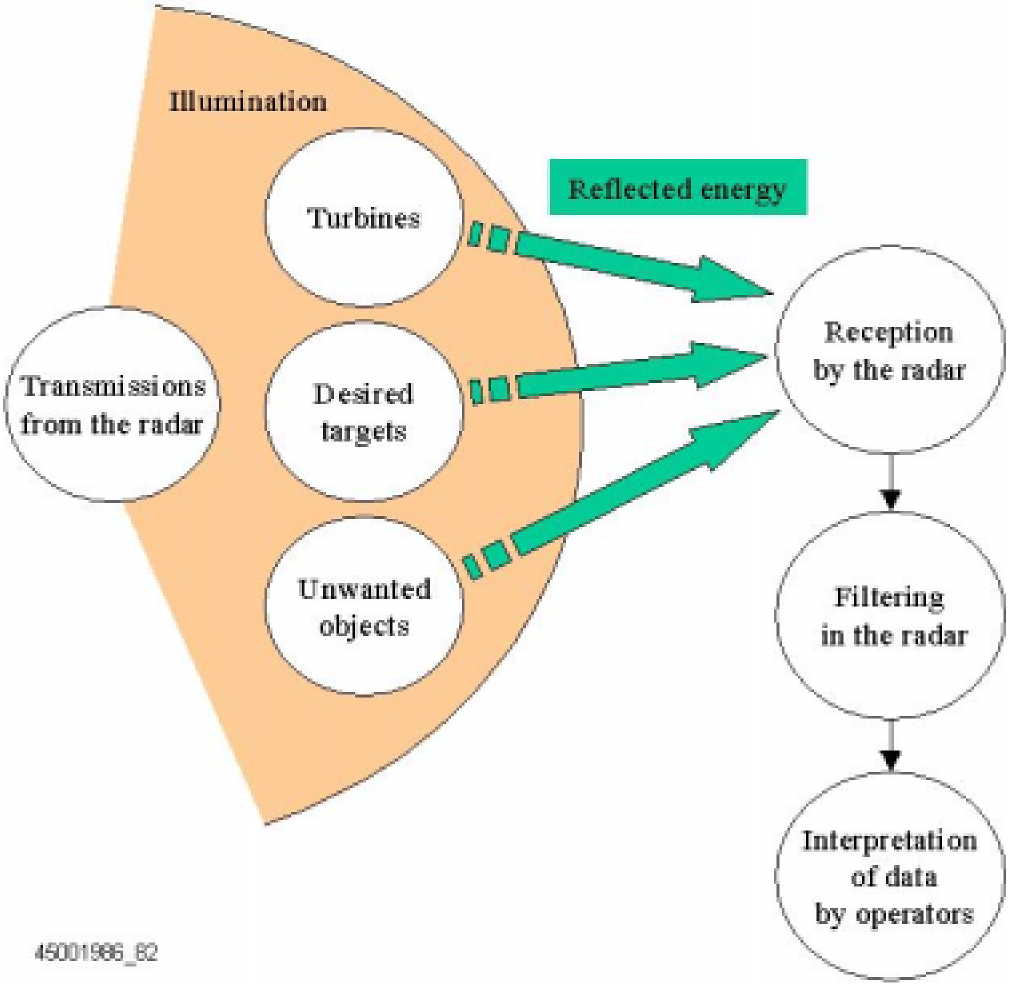

Figure 1.1 Definition of the Physical Problem Space

The radar illuminates all objects that surround it; the radar receives some of the reflected energy and then electronically filters the signals in a number of ways. Typically, an operator interprets the information that outputs from the radar, and uses this information as an aid to the decisions he must make.

1.8.2 System space

The objects in our problem space and the relationships between them are shown in the diagram Figure 1.1. The rest of the system is really only the internal workings of the radar. For the purposes of this study the radar is composed of a generic antenna/receiver/detector system with optional filters that will be chosen to represent the actual radars identified as affected currently. Filters will represent typical signal processing functions such as Pulse Compression, STC, CFAR, MTI, MTD, RAG, Plot Extraction, Plot Filtering and Track Extraction.

1.9 Problem Geometry

The physical geometry of the radar relative to the objects of interest is important when analysing the response of the radar. The physical phenomena that are relevant are explained below. For the purposes of this study, the problem geometry included the following objects:

- The turbines.
- The targets (eg aircraft under control or advisement).
- Other targets (eg aircraft not under control or advisement)
- Clutter (the generic term for the returns from the ground, the sea surface or man-made objects).

A plan view of the geometry of these objects relative to each other is depicted in Figure 1.2. A significant characteristic of the geometry is the angles of incidence between the turbine axes and the vector from the radar to the turbines since it can affect the ability to detect aircraft in the vicinity of the turbines. Additionally the geometry can affect the number of turbines declared erroneously as 'stationary aircraft'. A more detailed explanation germane to the geometry and effects upon radar performance is provided in Appendix F, Filtering Methods.

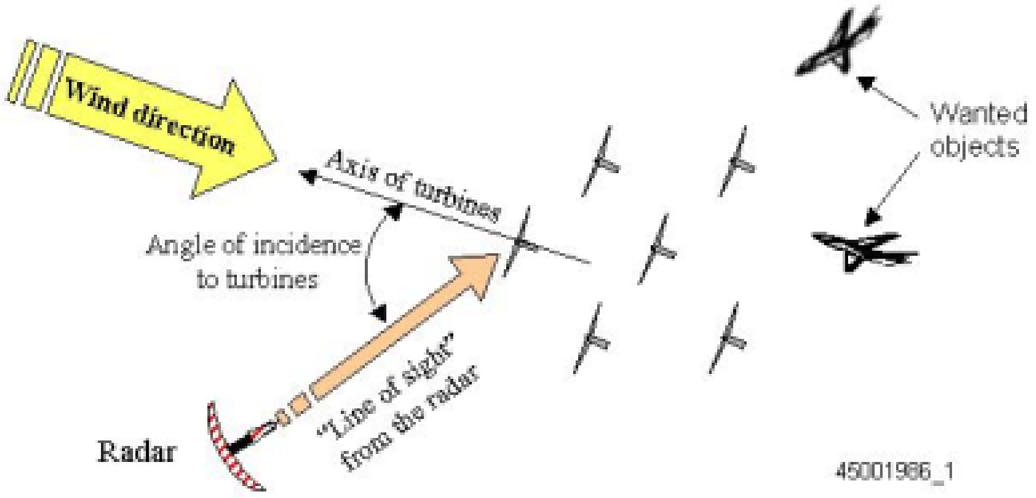

Figure 1.2 General Geometry of the Problem - Plan View

Terrain will also have an effect on the problem geometry. Terrain features such as hills, mountains, valleys and man-made objects such as buildings will limit the illumination of objects behind these features. The term "shadowing" in this context describes areas that are in the shadow of these features. Where the wind turbines are installed in areas that are shadowed, then they may be only partially illuminated or totally obscured. This is depicted below.

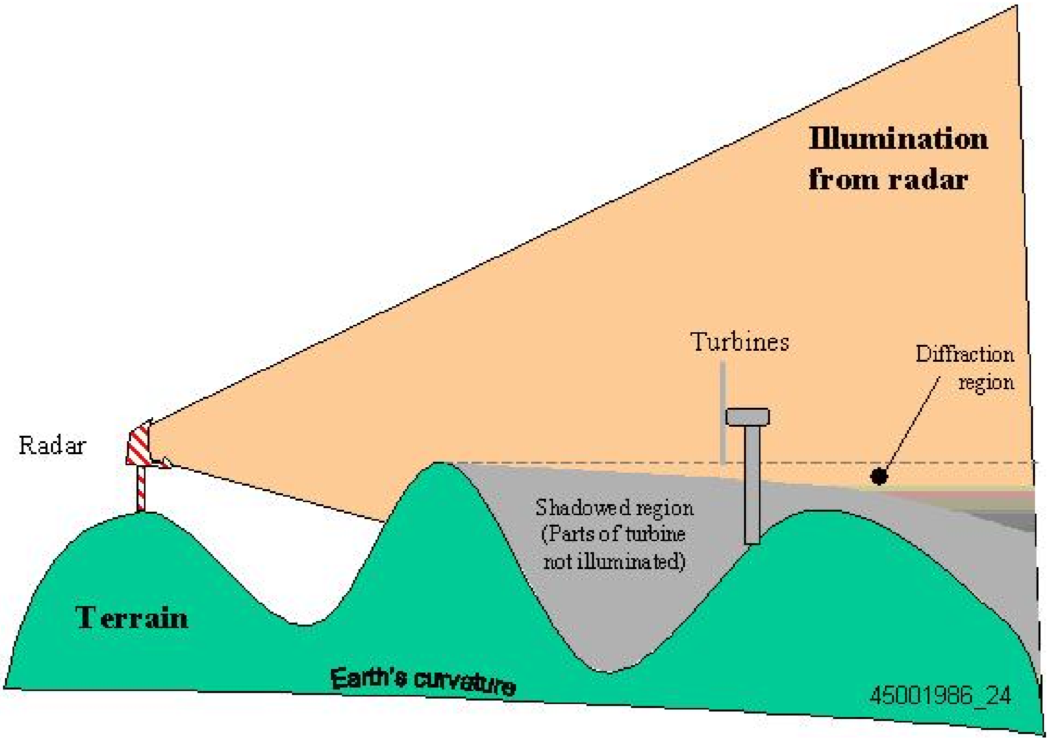

Figure 1.3 General Geometry of Energy Propagation and Terrain Shadowing

Although electro-magnetic energy travels in straight lines in free space, in the atmosphere and in the presence of opaque objects such as buildings and hills, propagation follows curved paths. Two effects; refraction and diffraction can cause this bending of the propagation path. These two effects are explained in Appendix A in more detail, but the effects caused are as follows.

Refraction causes the propagation paths to bend back toward the Earth's surface changing the apparent distance of the horizon. At radar frequency bands, distances are calculated using a "four-thirds" earth radius model. Throughout the report a letter is used to designate the frequency bands. See Reference 13.

Diffraction occurs where part of the radiated wave-front is obscured by an opaque object. An apparent bending of the propagation path occurs at the edge of the object, and objects that lie behind the obstruction are illuminated. This is shown diagrammatically in Figure 1.3 above. Reciprocal transmission of the reflected energy occurs back to the radar and thus objects that might be thought to be out of the line of sight of the radar, may still be detected.

When turbines are located behind hills, diffraction may under some circumstances allow the turbines to reflect but with a reduced RCS compared with free-space conditions. If the turbines are sufficiently deep in the shadowed region, they will be totally obscured.

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SECTION 2

WIND TURBINE DATA

2.1 Types of Turbine

There are many manufacturers of turbines, but in the class that may be called high power generators, the construction methods have converged over the years to a common approach. Typically modern turbines are of the horizontal axis type using two or three blades that rotate in the vertical plane. The electrical generation equipment is housed behind the blade-hub in an enclosed structure that can be rotated about the vertical axis to orientate the blades into the wind. The housing is mounted on the top of a cylindrical or gradually tapering tower usually of hollow steel construction.

Alternative constructions are used in some installations, but none of these have been identified in UK installations.

- Types where the blades rotate about a vertical axis appear to have fallen out of use and so have not been studied.
- Lower powered turbines, typically less than 300kW, may use towers of open lattice construction, sometimes very low power turbines use guy wires to steady the tower. The radar characteristics of these towers will be quite different to the solid cylindrical tower, but they have not been included in the study since it appears that their use is restricted to isolated rural applications in the USA.

It appears that many new turbines are being designed to operate non-synchronously with the mains supply frequency. Frequency conversion equipment is used to allow connection to the national grid system. This means the rotation rate of the blades is allowed to vary and different turbines in a wind farm will rotate at different rates. Since this is a more general case, the study has assumed that turbines in a farm will not rotate synchronously.

2.2 Generic Turbine Model

The surveys of turbine sites and of manufacturers' data have revealed a variation in construction details and a trend in growing sizes of turbines. To make this study as realistic as possible, it was decided to use a typical turbine from the high end of the range of power/sizes available. Meetings with one manufacturer (Reference 15 and Reference 21) indicated that the turbine chosen was perhaps not the largest that could be envisaged. Results of the modelling are presented in Appendix C, RCS Modelling Results and Spectrum Measurements.

The generic turbine that has been modelled is taken as a typical horizontal axis turbine. Scaled drawings of a proposed Offshore Wind Farm Turbine were used to produce a representative geometry using PATRAN – a 3-D CAD package.

2.2.1 Generic turbine CAD model

To model the RCS characteristics of an object, a CAD representation is first generated based on the structure shown in Figure 2.1. This representation then provides an input to the RCS modelling tool so the RCS can be predicted for a wide range of radar operating frequency bands, observation angles and orientations of the various parts of the turbine.

In basic terms the Radar Cross Section (RCS) refers to the ratio of power density, reflected by an object in the direction of the radar, to the transmitted power density incident upon the object. It should be noted that the RCS, generally stated as metres squared (m^2), is not the physical area of the object.

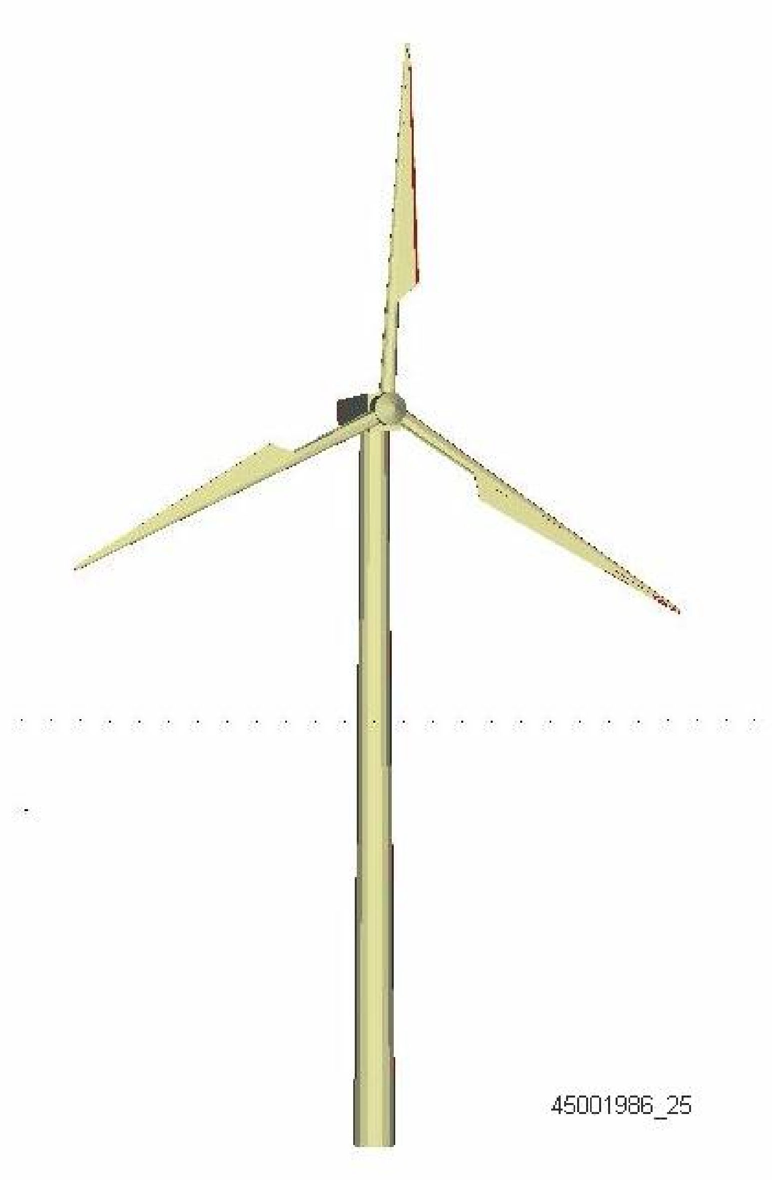

Figure 2.1 CAD Representation of the Generic Turbine

2.3 Observations on Turbine Characteristics

It will be obvious that different manufacturers use different construction techniques and materials. These lead to significant variations in the radar echoing characteristics as explained in Appendix B. Not only are materials a significant factor, but also shape. Details of the construction will generate significant variations in the radar characteristics. As an example, the construction and shape of the meteorological instrument cluster in the turbine illustrated in Figure 2.2 resembles a corner reflector, an efficient radar reflector that could produce a significant radar return even though it is not physically large. Within this generalised study it is not possible to model all the variations so the generic model above has assumed a featureless nacelle structure.

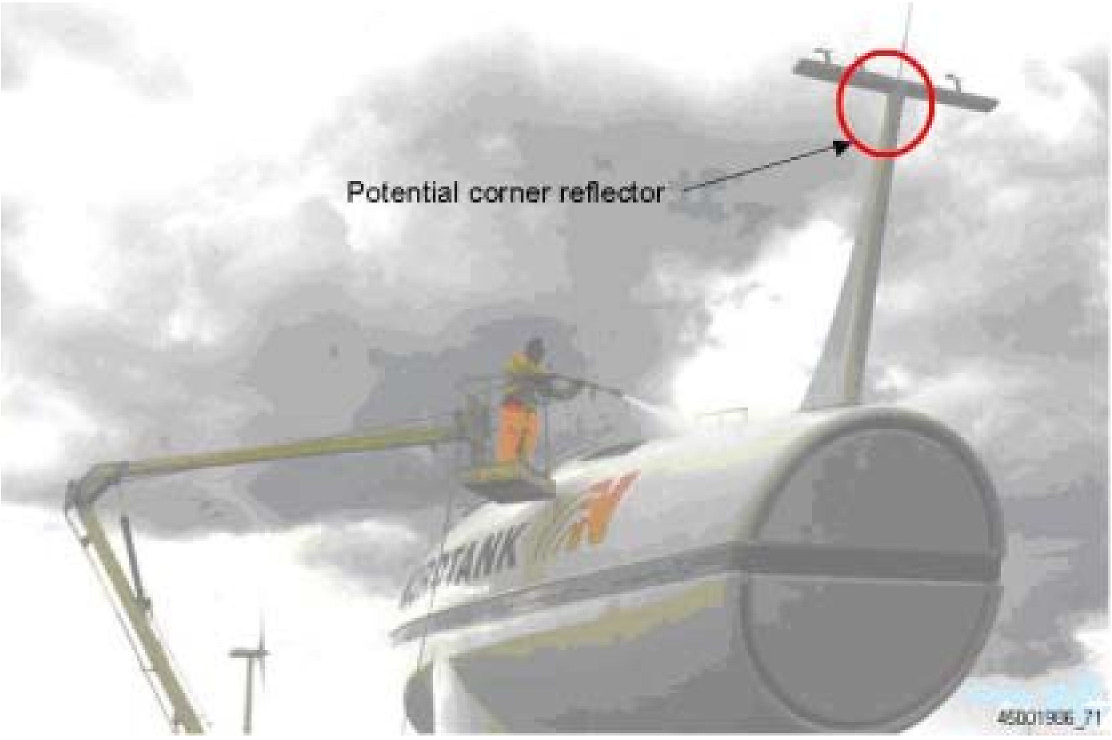

Figure 2.2 A Typical Corner Reflector that may Produce Significant Radar Returns (Photograph courtesy of NEG-Micon)

Trends in turbine design are clear, larger turbines are more cost effective and blades of 65 metres length are in production now (Reference 21). The scope for installing these turbines both on-shore and off-shore is improving with sectional blade designs allowing transport by road.

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SECTION 3

THE RADAR CROSS SECTION, DOPPLER EFFECTS AND OTHER CHARACTERISTICS OF WIND TURBINES

3.1 General Characteristics

This part of the study looked at several characteristics of wind turbines. Radars are in general designed to operate in the presence of large structures with limitations on size and distance from the radar. It is important to note that the structures of wind turbines, not only because of their physical size but also because of the shapes and materials used, are significantly different to buildings and other structures such as electricity pylons, large chimneys, etc.

The characteristics that have been examined in this part of the study are:

- Radar cross section - this is composed of a number of elements that have been studied separately and as an entity
- Doppler modulation of the reflected signal
- Modulation of the reflections from objects behind the turbine
- Shadowing of areas behind the turbines
- Re-reflections of the energy from other objects by the turbines

3.2 Farms of Turbines

Where multiple turbines are installed, the area enclosing the farm may be very large. Turbines are separated by distances dictated by local terrain features and the desire to minimise the effect of airflow disturbances on successive turbines in the flow. Figure 3.1 shows a typical wind farm cluster.

Reference 11 indicates "They are usually spaced 2-3 diameters apart in the cross-wind direction and 5-10 diameters apart in the downwind direction, with respect to the direction of the prevailing wind".

In offshore installations the terrain effects are limited to consideration of the geology and topology of the seabed.

Figure 3.1 A Typical Wind Farm Cluster - Dun Law Wind Farm
Photo courtesy of Renewable Energy Systems

3.3 Radar Cross Section

In this part of the report, the reflection characteristics of the turbine chosen to be representative are described. Radar Cross Section or RCS represents the radar reflecting area thus the greater the RCS the greater the signal level returned to the radar. These characteristics have been derived mostly using a standard commercially available RCS modelling tool known as "Epsilon" (Reference 14). This tool has been in use for many years and is highly respected within the industry.

3.3.1 Bulk Radar Cross Section

The bulk RCS is strongly aspect dependent and is a strong function of the materials and shapes of all parts of the structure. It has been found that there are three significant contributors to the bulk RCS observed by a radar:

- The support tower
- The nacelle
- The blades including the rotating hub

3.3.1.1 The support tower

This is the most significant object since it is physically large and constructed of materials that are good radar reflectors. The RCS of the support tower is easily estimated (to a first order of accuracy) using standard formulae. This indicated that the RCS is extremely large compared with the normal objects an ATC radar is designed to work with. A theoretical RCS of 3 million square metres is typical of a 100 metre high tower at S-band (see Appendix A). Compared with a large aircraft, presenting an RCS of 100 square metres, the signal level returned from the tower could be 30,000 times greater.

The modelling of the typical tower produces an RCS much less than this figure because the tower is tapered and the slope of the sides of the tower reflects the radar energy slightly upwards from the horizontal. This slope is just sufficient to move the peak of the RCS upward away from the direction of the radar, but will be obviated if the tower bends due to solar heating or wind loads.

Maximum reflected energy from a cylindrical or conical shaped tower back to the radar occurs at right angles to the surface of the structure, as shown in Figure 3.2. The illustration in Figure 3.2 assumes the radar illuminating the tower also receives the reflected energy. Since the tower in plan view is circular the pattern in elevation will be the same at any angle in plan around the tower. The pattern representing the profile of the reflected energy in elevation, as a function of elevation angle, appears as a main lobe but accompanied with lower level minor lobes or sidelobes, also shown in Figure 3.2. It is usual to express the width of the main lobe at the points corresponding to 50% of the peak response. Crucially the main lobe width in elevation is narrow for reflections from a tall tower and corresponds approximately to 0.3° at L band and 0.1° at S band for a tower 100 metres high. It should be recalled that the level of energy reflected is directly related to the Radar Cross Section or RCS. Appendix C, RCS Modelling Results and Spectrum Measurement, portrays two plots indicating the modelled RCS of a tower as a function of elevation angle.

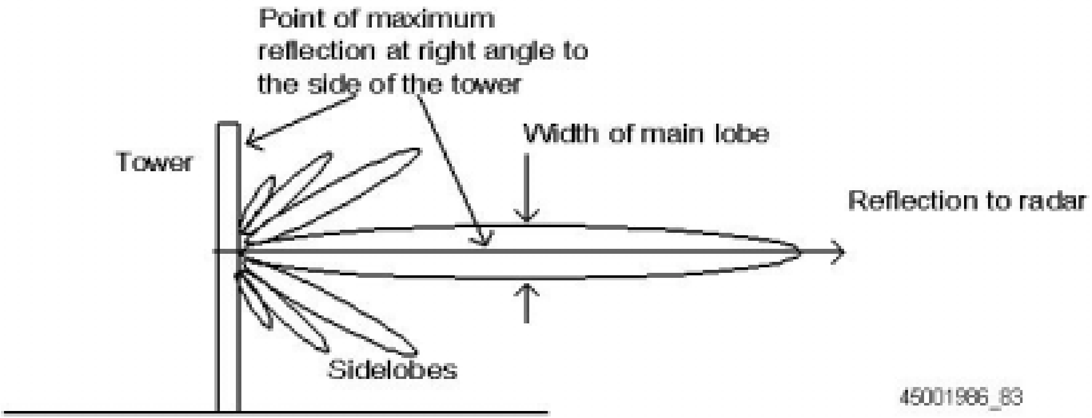


Figure 3.2 Angle of Maximum Reflection back to the Radar Shown in Elevation

The specimen tower diameter reduces by about 1.5 metres over its 90 metre length, ie the sides slope by 0.5° in elevation. This provides a reduction in the RCS assuming the tower is observed from a horizontal aspect. This reduction in RCS is less for the long-range (En-route) radars operating at L band than for the terminal radars operating at S because the width of the RCS main lobe is greater at the lower frequencies. The corollary is that increasing the taper angle of the tower, with the RCS perceived in the main lobe, will reduce the reflected energy from the radar assuming the radar is positioned in a straight line at a right angle to the perpendicular of the tower.

Figure 3.3 is a plot of the RCS presented by a tower and turbine as observed from any angle in plan view around the tower. Compare these results with the theoretical peak values for the tower 65dBsm (3 million square metres) at S-band and 60dBsm (1 million square metres) at L-band. The differences are due to the slope of the tower sides and are very sensitive to the precise slope angle. This slope will of course vary with slight errors in tower installation, bending due to wind and solar heating effects.

The sensitivity can be seen in the difference between the L-band general level (about 30dBsm) and the general S-band level (very approximately between 10 and 20dBsm). This is due to the L-band angular response of the tower being a wider angle in the elevation plane (ie at right angles to the plot shown). The tower response therefore dominates at L-band. Appendix C, RCS Modelling Results and Spectrum Measurement provides a detailed description of the RCS modelling.

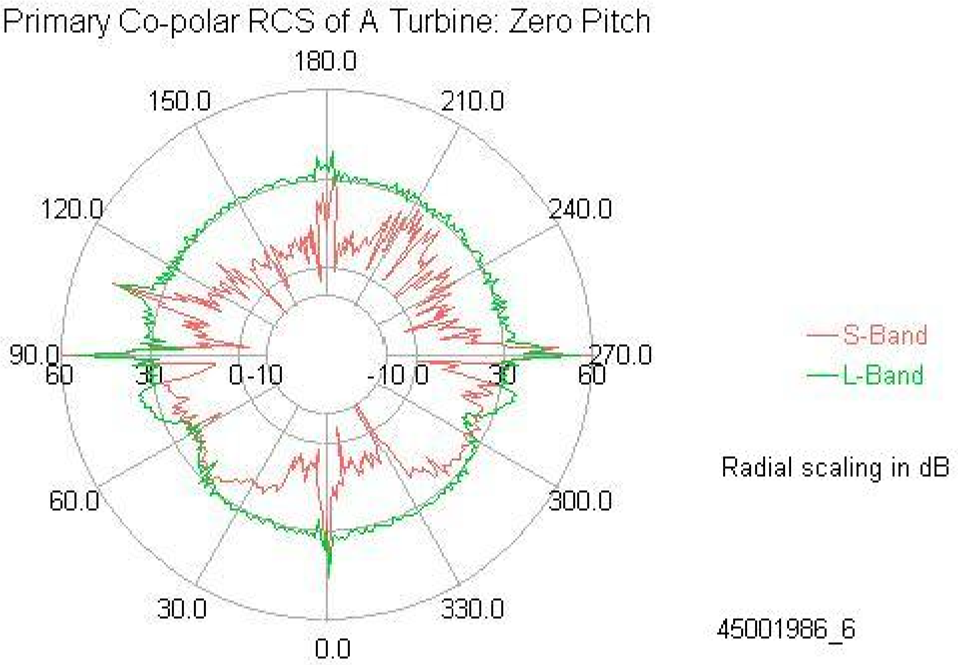


Figure 3.3 Example RCS Modelled on a Turbine Observed from 360° Around the Tower

3.3.1.2 Tower Bending

Typically a 100m long tower will move 0.4 metres horizontally under maximum wind conditions. Similarly when the sun is shining on one side of a tower, the differential expansion of the tower causes a similar movement of the top.

These movements will cause a curvature in the tower, which will modify the shape of the tower's directivity (RCS against angle of view) and will cause the angle of the peak in directivity to move downwards away from the direction of the wind. The downward deflections in both of these cases will be approximately 0.2°.

These provisional figures indicate that bending can occur that is of the same order of magnitude as the taper on the tower sides and the width of the directivity peak in the RCS response. This indicates that the RCS as observed by a radar can be expected to change by orders of magnitude.

3.3.1.3 The Nacelle

The nacelle is of significant physical size. In our simplified model this has been represented as a simple rectangular box with vertical sides. In practice the shapes and materials are very varied. The nacelle has been assumed to be smoothly clad in a conducting material for the purposes of this study. In retrospect, a more sensible concept would have been to assume a degree of "radar friendly" design in the nacelle with the vertical faces at a slope of a few degrees.

The presence of structures on the turbine head such as lifting gantries will complicate the RCS models beyond that which could be achieved in the study timescales. Similarly the decision to model the nacelle as constructed from conductive materials is not representative, but to model the complex shapes that exist within the nacelle interior would have been prohibitive within the small study budget. The modelling method however is deemed sufficient to provide indicative results.

3.3.1.4 The blades

The blades present a smaller surface area than the tower, curvature of the blade surface is more complex and so reflections are "focussed" in dispersed directions relative to the blade surface.

The rotation of the blades causes two effects to the bulk RCS; a time modulation of the return signal as the blades present varying aspect angles, and a modulation or "chopping" of the RCS of objects behind the blade. The latter is dealt with separately below.

Variations of the blade aspect angle cause the RCS to vary, sometimes if a significant peak in the RCS exists at some combination of angles, then this is observed as a sudden peak in the reflected return, referred to as a "blade flash". This is caused by the curved surface of the blade, the curvature causes the return characteristic to be non-isotropic, with peaks in certain directions with respect to the blade axis.

The joint probability that the radar will have transmitted in the direction of the turbine at the precise time that the peak of the blade RCS passes the reciprocal direction is very low. This probability of intercept cannot be quantified since it is dependent on many factors specific to the radar, turbine and relative locations.

Blades can present a significant RCS at other angles than those corresponding to the peak, thus the probability of detecting the turbine blades will not be solely dependent on intercepting the peak RCS. A large variation in the returned signal level from the blades can be expected with potential to exceed the design limits for linear operation of the receiver and signal processing, depending on the RCS and range from the radar. The consequences of exceeding the design limits will be loss of detection and breaking track.

Blade geometry is not constant; several effects cause the blade geometry to change. Deliberate mechanisms that are not a feature of all turbines include:

- Blade pitch adjustment to regulate the torque generated in the turbine. This will be a function of wind speed and electrical load demand. At high wind speeds the blades are "feathered" presenting a small surface area in the direction of the wind vector.
- Mechanisms used for air braking which cause plates or sections of the blade tips to rotate.

Variations will also occur due to bending of the blades and the support tower under wind forces and to a lesser extent under differential solar heating.

The characteristics of the blades will therefore vary from time to time. Changes to blade pitch have been included in the generic model, but none of the other mechanisms are modelled.

3.3.1.5 Note on RCS predictions

The fitting of external access ladders and handrails for instance appear insignificant but can cause large changes to the RCS. These effects have not been included in the RCS modelling because of modelling of such detail requires specific measurements, is labour intensive, computationally intensive and will be specific to the actual mechanical configuration (Field measurements conducted under a separate study will certainly include the effects (Reference 17)). The effects are dominated by the presence of the angled corners between parts of the metalwork, these corners can cause disproportionately large responses (an effect that is exploited for instance in the "corner reflectors" fitted to small boats and to radio-sonde balloons). See Figure 2.2 for an example.

3.4 Observations on the RCS Characteristics of Turbines

The significance of the RCS figures detailed above is explained in the following section regarding the effects on radar. What is evident from the part of the study concerned with RCS modelling is that the bulk RCS of the tower is extremely large and is only reduced to manageable proportions by the fact that the tower is tapered. This taper presents a slightly sloping side aspect, offsetting the peak in RCS response by a small angle that just avoids any adjacent radar. The offset is extremely small and significant changes in observed

RCS will occur due to slight movements of the tower due to wind or solar heating. This aspect warrants consideration in the tower design to make the towers more "radar friendly".

The RCS of the nacelle will be highly dependent on both shape and material. Some gross assumptions made for this study show very high RCS values, of the order of 50dBsm or 0.5 million square metres. Current designs of nacelles where there is no control of the RCS will exhibit very variable RCS values with high variation with aspect angle. It is safe to assume that the absolute RCS values of current nacelle designs will be less than the gross figure calculated above. Nevertheless, some control of RCS by design will be desirable.

Blade characteristics are much more complex than the simple shapes of the tower and nacelle. The blades are of particular interest in this study as they are moving with tip velocities comparable with the speeds of aircraft on final approach and with small aircraft in cruise. The aerodynamic requirements for blades mean that using shape techniques to minimise RCS is not an option. Their complex internal construction and variation between manufacturers also means that characterising the RCS of blades by modelling is uncertain. Future trend towards Carbon Fibre will mean that the outer skin of the blades is essentially conductive and therefore highly reflective at the radar frequencies of interest.

Small features such as ladders, brackets, doorways and anemometers will produce disproportionate RCS values compared with their physical size. This is because of the reflecting and re-radiating mechanisms that take place. It will be important to minimise the effects of these features in a "radar friendly" design using basic stealth techniques.

3.5 RCS of Multiple Turbines

Turbines are spaced a considerable distance apart (in radar wavelength terms) so the cumulative effect will comprise an effectively random summation of the reflections from each turbine. The reflected signals will combine in the radar antenna but since the phases and amplitudes of these signals will be highly variable, the summation of coincident pulses will vary from complete addition to complete cancellation and all values in between.

3.6 Doppler Modulation

3.6.1 Single turbine

The component of the velocity of a moving object along the line of sight to the radar generates the Doppler frequency shift effect. Nearly all ATC radars have processing channels that are designed to pass reflections that have significant Doppler content. This is used as a way of rejecting objects that are not moving, for instance, ground clutter. The key characteristic is the velocity of any moving part along the line of sight to the radar. Various parts of the turbine will exhibit movement at different times and at different rates but only the blade rotation is considered to be significant in this study.

The rotation of the tower head to follow the changing wind direction (yaw) is slow and will not generate a significant Doppler component. Similarly the rotation of blades about their own (pitch) axes will be slow (as the control mechanism adapts to varying wind speed and electrical load demands).

Any rotating parts within the nacelle (shafts, generator armatures, etc) may be visible through the head housing if its cover is radar transparent (such as thin GRP). This may cause Doppler components to be generated. Within this study this has not been examined in detail, the mechanical models would be complex and would required detailed definition to make a radar model of sufficiently high fidelity. For other reasons it would be better to enclose the nacelle in reflective material so that the RCS can be controlled and managed by design.

In the context of wind turbines it is only the blade rotation that causes significant velocity components. When observed from the radar at right angles to the axis of rotation the blade velocity can vary from zero at the root to a maximum at the tips. In this case the tip velocity can be typically 50 metres per second or in future designs maybe up to 80 metres per second. This velocity lies within the velocity band that ATC radars are designed to detect and pass to operators (aircraft speeds typically lie between a few tens of metres per second up to an extreme of several hundred m/s at cruise altitudes).

The strength of the Doppler components is a function of the reflectivity (RCS) of the object and so is dependent on construction and shape just as is the bulk RCS.

3.6.2 Multiple turbines

Compared with a single turbine the spectrum from a collection of turbines will be more complex. In some turbine designs, rotation speeds are fixed within a few percent whilst the turbines are generating, in other designs rotation speed can vary widely. The rotations will not be perfectly synchronised so both an interference effect and randomisation of the chopping effect will occur. Where turbines with variable rotation speed are operated, the randomisation will be much greater and will vary with operating conditions.

Also within a wind farm not all turbines will be aligned to the same direction, variations in the wind direction across the breadth of the farm will cause turbine directions to vary widely.

3.7 RCS Chopping

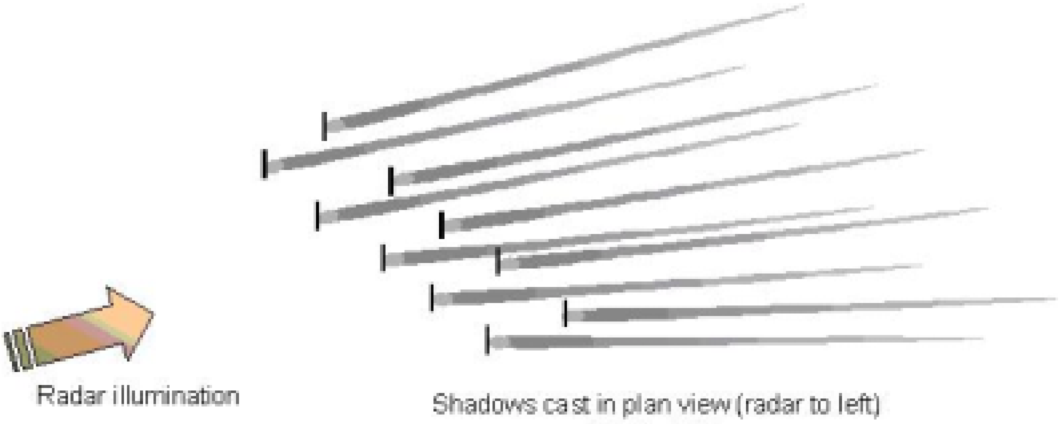
RCS chopping occurs because the blades intermittently obscure the returns from other objects. The effects on radar are considered to be insignificant, as the spectral spreading from the chopping effect causing amplitude modulation will be low.

Where turbines with variable rotation speed are operated, the randomisation will be much greater and will vary with operating conditions. This effect has been discussed in Reference 12, but to quantify this effect would require separate detailed study.

3.8 Shadowing

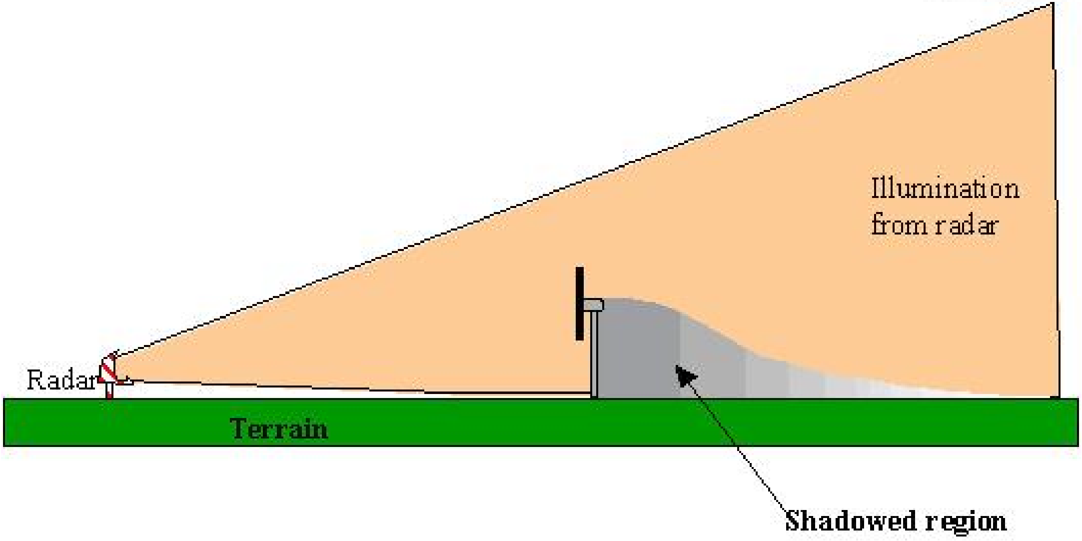
Objects that lie behind the turbine (from the perspective of the radar) may lie in the shadow of the turbine. Propagation of the radar energy behind obstructions is covered in many of the standard radar texts (Reference 22 for instance). The effect on a wavefront partially obstructed by an obstacle is generally referred to as "diffraction" and the effect causes an apparent bending of the direction of propagation of the wavefront. The results of this bending is that (in contrast to the shadow that would be generated by a light source) the energy behind the obstacle is higher that would be expected. In effect the shadow is partially filled.

The energy that has been blocked by the turbine is of course lost by reflection in other directions. The energy that partially fills the shadow region behind the turbine is taken from the energy that passes the turbine unobstructed, so the field strength behind the turbine is diminished over a region that shrinks with range behind the turbine. This situation is shown pictorially in Figure 3.4.



Shadows cast in plan view (radar to left)
Not to scale

45001986_26



Shadows cast in elevation view
Not to scale

45001986_27

Figure 3.4 Shadowing of the Space Behind Turbines

Reference 17 calculates that the echoing area of a target 1 km directly behind a single typical turbine is reduced by 6dB (ie to one quarter of the signal strength that would be expected if not obscured). At ranges greater that this, the echoing area reduction becomes less, and at very long ranges the reduction becomes 2dB, ie a reduction of about 35%. Where turbines are clustered then this effect is compounded by the diffraction round each turbine, and the dimensions of the resulting shadow will be a function of the "width" of the turbine cluster (See Figure 3.1).

In practice, the field strengths that are present close to the terrain surface are affected by many other factors as well, including the reflective properties of the surface, its roughness, etc, so modelling exact field strengths in these regions is not an exact science.

It is important to realise that shadowed areas are only significant if they extend into regions where it is important to maintain radar coverage. Since the turbine heights are very small compared with the typical flying altitudes of aircraft, then this situation is unlikely but would required to be investigated for any potential wind farm.
(See Figure 3.4).

The proportion of the volume behind the turbines that is shadowed is obviously a function of the numbers and size of the turbines and their disposition with respect to the radar.

The effect that shadowing will cause may be more of an issue for radars used for defence purposes where hostile aircraft use the (predictable) shadows to hide their approach and where the RCS of the hostile targets may be much smaller than the values used typically for ATC radars. It is also an issue for ATC radar where small uncontrolled targets may appear unexpectedly at short range as they pop-up from the shadowed region. This problem of course already exists where shadowing occurs due to terrain features. Radars are sited to minimise the shadowing of important areas and directions, and procedural methods are used in the ATC environment to minimise the impact on shadowing to safety, etc.

Where objects cross the boundaries of shadowed areas, there may also be effects on the angular position reported by the radar. These will probably not be of concern in an ATC role, but would be of concern if the radar has a precision tracking function. This function is likely in military radars associated with weapons systems but may be significant if precision approach radars are used.

3.9 Reflection Effects

Where multiple turbines are installed, and the material of the turbine towers is a good reflector such as steel, then it is possible for the energy from the radar to be reflected from tower to tower and then onto objects behind any particular tower. Similarly the reflected energy from an object may be re-reflected from the towers and arrive at the radar from an unexpected direction. The effects that this type of reflection will cause are:

- Objects thought to be shadowed are in fact visible
- Objects pop in and out of visibility as the turbine blades obscure reflections from other towers.
- Objects appear displaced because the direction of arrival at the radar is via a reflected path.

These effects are limited to objects at very low altitudes.

There are observations of reflections from turbines causing aircraft to be reported at grossly wrong bearings (Reference 16). Predicting the effects due multiple reflections will be practically impossible since the shape of the turbine is multi-faceted and complicated. Mitigation is possible by designing particular components of the wind turbine to reduce the reflectivity.

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SECTION 4

RADAR TYPES AND CHARACTERISTICS

4.1 Survey of UK ATC Installations

4.1.1 Radar roles used in ATC

A wide range of equipment used for ATC purposes in the UK can be described as radars. There are also equipments that use radio transmissions for ATC purposes that are definitely not radars. Some of these equipment types are identified in Appendix D. The study has then examined those systems that are clearly radars used for ATC purposes.

Within the class of equipment identified as ATC radars, each radar may provide data to different operators performing different roles, the radars can thus be identified by the roles that they support. In general (but not always) different classes of radar are used for each role but sometimes quite different radar types can be used for the same role. The type of radar chosen for a particular role is driven as much by the local conditions and air traffic situation as by the specific role. Thus there is not just one radar type for each role, and sometimes radars are dual role.

In order to identify the data (or services) expected from radars, the roles have to be defined. We have chosen to describe the roles from the CAA regulations (JAR-LFC 062 for instance) as follows in Table 4.1:

RSR	En-route Surveillance radar
TMA	Terminal Manoeuvring Area radar

Table 4.1 Roles of ATC radars

RSR and TMA are stated in the CAA Joint Aviation Requirements (JAR) document regarding the Airline Transport Pilots Licence (060 00 00 00 - Navigation). JAR-FCL reference 062 02 02 00 lists the learning objectives under Ground Radar as Principles, Presentation and Interpretation, Coverage and Range, Errors and Accuracy and Factors Affecting Range and Accuracy.

Two other ATC roles have been identified in particular as potentially vulnerable, but lie outside the scope of this study:

- Airport Surface Detection Equipment (ASDE)
- Precision Approach Radar (PAR)

The radars used for the control of aircraft when on the ground and to detect airport intrusions and known as Airport Surface Detection Equipment (ASDE) are potentially vulnerable by virtue of their fairly unsophisticated processing. They are however very short range and would only suffer effects due to ambiguous range detection of the turbines.

A further class of radar used exclusively by the military but available for civilian use in emergency situations is the Precision Approach Radar (PAR). This type of radar is used in conjunction with surveillance radar to assist the assist the controller in 'talking down' the aircraft pilot. The technique is referred to as Ground Controlled Approach. Azimuth and elevation precision of aircraft location could probably be affected by wind turbines.

Additionally there are commonly used landing aids that rely on the transmission of RF beams from ground equipment and "beacon" systems such as VOR. The precision of the beams used in landing systems is of paramount importance to aircraft safety. Two landing systems that are in use are the Microwave Landing System (MLS) and the Instrumented Landing System (ILS).

4.1.2 Civil and military use

Both the military and civilian uses of UK airspace are controlled using similar procedures and similar radar equipments. The RAF does provide some data for civil ATC purposes from its own ATC radars, and NATS provides some cover for a small number of MoD sites that may require safety control of their air space. There are differences in the configurations of radars used by the military that are subject to security restrictions. The most significant difference is that many of the military radars are mobile and so any setting up for any specific location is done differently and the radars may incorporate automatic processes to deal with varying operating conditions. In general the behaviour of defence radars in the presence of wind turbines is covered in this report, but performance aspects that relate to the military functions are not covered in this report.

4.1.3 Summary of ATC radar type in use in the UK

Radars operational in the civil sector are summarised in Table 4.2.

Type identification	Manufacturer	Description
Watchman T	AMS	S-band TMA
Watchman S	AMS/Thales	S-band TMA
S511(EN4000)	AMS	S-band TMA
S511H /Surveyor	AMS	S-band TMA
AR1/AR15	AMS	S-band TMA
CAARP	HSA/TST	S-band TMA
Routeman	AMS/TST	L-band en-route
AR5/AR51	AMS	L-band en-route
ASR 10-SS	Raytheon	S-band TMA
ACR430	AMS	X-band short range TMA

Table 4.2 Radar Equipment Types (civil En-Route and TMA only)

The variety of these radar types is compounded by the fact that some have been in service for a long time, and many upgrades and changes in design have occurred. Each radar installation must therefore be considered carefully to define the build-state and condition of the equipment before any modifications can be considered.

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SECTION 5

RADAR PERFORMANCE MODELLING RESULTS

5.1 Phenomena Modelled

There are two basic effects that need to be considered

- Generation of False alarms
- Reduction in detection performance

The definition of false alarm is complex, basically any detection that is an object that the operator does not want to see can be categorised as a false alarm and this means that the definition of a false alarm will depend on the application of the radar. Sources of false alarms include the thermal noise mixed in the received signal, and detections of "clutter" which can be land, sea. rain, moving traffic, etc. Each source of false alarms is considered and where possible, the effects estimated. Noise generated by the radar system is the parameter that generally enables the Probability of False Alarm (PFA) to be estimated. PFAs can be estimated for most conditions provided these conditions are known in detail. Examples of a general case are homogenious land surface, homogenious rain conditions and homogenious sea conditions. If the clutter conditions are variable with time, as in the case of the wind turbine, or not defined then it is not possible to generally estimate the PFA.

Radars include many features to control the generation of false alarms, some of these are automatic and respond to the presence of clutter by adjusting the detection process within the radar. The approaches to false alarm control are different between civil and military applications with less emphasis on automatic control in civil use. Any process that reduces the radar's sensitivity in order to control false alarms will also affect the ability of the radar to detect aircraft.

MTI and MTD processing is incorporated into many ATC radars to discriminate between returns from a stationary and moving object. This type of processing enables the operator to observe representations on the display of moving objects only without being 'cluttered' by responses from stationary objects.

5.2 Modelling Techniques

Radar emissions can be echoed from both the static parts and the moving blades of the wind turbine. Echoes from the static parts, such as the tower and nacelle, are not offset in frequency whereas echoes from the moving blades are offset in frequency due to the Doppler effect.

Radars configured without MTI/MTD or other sophisticated processing will only sense the reflected signal from the moving parts of the turbine as probable changes in magnitude. In contrast radars configured with MTI/MTD processing are designed to indicate or detect moving objects such as aircraft.

MTI processing is intended to differentiate between a moving object and a stationary object coincident in range and bearing, thus it is not possible to differentiate between returns from the moving turbine blades and a moving aircraft as both returns have imposed Doppler. MTI filters only provide a null or 'notch' in the response to filter out returns from static or very slow moving objects. As the spectrum from the turbine blades is likely to be much wider than the 'notch' then MTI is ineffective at resolving just an aircraft.

An MTD performs in a similar manner to the MTI except it is configured as a bank of Doppler filters to shape the response. The filter with the greatest magnitude is selected to provide the output data but as in the case of the MTI processor the MTD as currently configured is unable to discriminate between aircraft and turbine Doppler frequencies. As the velocities along the length of the blade, with respect to the radar, range from near zero to the tip velocity then a corresponding range of Doppler offset frequencies are imposed. Thus all the MTD filters could be filled with data representing the return from the turbine. It should be noted that responses from turbine blades corresponding to a radial velocity, with respect to the radar, greater than the first blind speed are expected to occupy all MTD filters. An explanation of blind speed is presented in Appendix E however for most ATC radars it is approximately $50ms^{-1}$.

The corollary is that both MTI and MTD processing will detect the moving blades as a moving object, despite not actually moving in range. Declaring the turbine as a moving object in radar terms may be considered a false alarm.

Many ATC radars are configured with a pulse compression network since the requirement is for a highly frequency stable transmitter design to improve the MTI or MTD process. A highly stable transmitter is normally configured with a high power amplifier, amplifying low-level signals. Unfortunately efficient amplifiers occupying minimal volume are incapable of producing high peak power although capable of achieving adequate mean power. This problem is overcome by transmitting a long pulse of RF but compressing the pulse in time upon return to obtain the required range resolution. The technique is not a panacea since time sidelobes are generated, that is, compressing the pulse is not perfect and a small amount of the signal is not compressed. Pulse compression is a linear process producing a narrow main pulse and low level time sidelobes extending over a time interval corresponding to twice the duration of the transmitted pulse. If the process becomes non-linear, for example due to amplitude limiting, then depending on where the non-linearity occurs in the system, performance can be degraded. Possibly the most significant effect is two overlapping received pulses with one or both being subjected to amplitude limiting before compression. As a consequence time sidelobe levels can rise significantly and 'ghost' responses can be generated. These erroneous responses can subsequently be detected and declared as a false alarm. The effect of amplitude limiting is easily modelled with computer software to provide representative results.

Amplitude limiting in a magnetron based radar does not present the same difficulties as the radar based on pulse compression, however the received narrow pulse can effectively broaden when in limit, particularly if the receiver filters are not matched to the received pulse. The consequence of a large signal causing limiting is the masking of smaller signals due to the width of the pulse in limit broadening. Appendix E, Radar Effects Modelling, provides a detailed description of amplitude limiting effects.

Erroneous responses arising from turbine blade echoes could be considered as false alarms but are actually detection of unwanted objects, for example, detection of hovering helicopters is considered valid in a military environment. False alarms are mostly considered as arising from system noise and system instability. False alarm rate is a crucial parameter often featured in the design requirement for the radar. Probability of detection and false alarm rates are a interrelated since increasing the detection probability, by reducing the threshold above which a target is detected, results in a higher false alarm rate. It is therefore crucial that the threshold is set to a level that produces an acceptable rate of false alarms so presenting a clearer radar picture.

Dedicated processing within the general radar signal processing attempts to maintain a Constant False Alarm Rate (CFAR) but is adversely affected by the large magnitude returns from the turbines; manifesting as a loss in detection. Keeping the model simple, the CFAR is set to a defined rate consistent with that normally adopted for an ATC radar based on system noise alone. This ensures that the probability of detecting an aircraft, as originally envisaged, is maintained in a non-cluttered environment.

Appendix F provides an estimate of how much the signal to noise ratio, a parameter to assess the probability of detecting an object, is likely to change as a consequence of a turbine affecting the radar performance. Results indicate that for the RCS figures stated in the report, a turbine reflecting a signal some 100 times greater than a signal reflected from an aircraft results in a loss of half the signal to noise ratio due to CFAR implementation. If the probability of detecting an aircraft is marginal then the effect of the wind turbine is likely to be severe.

5.3 Summary of results

Spectral content of the rotating turbine blades extends up to the Doppler offset frequency resulting from the blade tip velocity. Typically the first blind speed for an ATC radar is in the order of 50m/s but will be exceeded by the tip velocity of 80m/s, perceived as the design aim for a future turbine. The tip velocity is considered as radial with respect to the radar for the worst scenario but is actually dependent on the wind force and direction. Detecting an aircraft by the MTI/MTD process in the vicinity of a turbine will therefore not be possible under these conditions.

Effects of an echo equivalent to an RCS of 10^4m^2 causing amplitude limiting pre-pulse compression have been modelled for transmitted pulses of 50μs duration.

As an example a return from an aircraft with an RCS of $10m^2$, separated by 1km from a wind turbine indicates the aircraft return is attenuated by approximately 15dB although reducing (signal level increases) as the amount of overlap between the two pulses decreases. If the CFAR processing is unable to cope with the reduced level of signal and noise then the condition will result in reduced target detection.

Modelling indicates that two signals representing the echoes from two closely spaced objects with one or both signals in limit produce other frequency components that, depending on the characteristics, can be detected as moving objects. Actual data resulting from an MTI process confirms the effects indicated by modelling. Appendix E, Radar Effects Modelling, provides a more detailed explanation.

Appendix F, Filtering Methods also provides an account of modelled losses based on the modelled RCS results and a false alarm rate normally specified for an ATC radar in a non-cluttered environment. The results indicate a spread of 1.3dB to 5dB, equivalent to a reduced detection range for an aircraft of between .93 and .75 times the range before the loss.

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SECTION 6

SELECTION OF FILTERS AND METHODS OF MITIGATION

6.1 MTD processing

Signals returned from the turbine blades, with a blade tip velocity of greater than $50ms^{-1}$ and axis of rotation at right angles to the radar beam, are unlikely to be resolved by the MTD process.

In contrast if the axis of rotation is in line with the radar beam, then the Doppler frequencies are likely to be much less than the first blind speed. Therefore there is a probability that a moving aircraft in the vicinity of the turbine could be detected in the MTD channel provided the return from the turbine is not too large. Resolving an aircraft and turbine in the MTD channel would at least be dependent on the aircraft radial velocity, turbine axis of rotation with respect to the radar, blade tip velocity and received signal levels, including those returned from the static parts of the turbine.

Modifications to the radar would include selection of the MTD filters appropriate to the conditions in order that the turbine responses could be filtered. It is likely that filter selection would be performed by an electronic process and not by the operator. Implementation would affect the digital signal processor.

6.2 Constant False Alarm Rate (CFAR) processing

Modifying the CFAR processing is identified as a means of improving the probability of detecting aircraft in the presence of high level signals returned from a wind turbine.

The average background level, which determines the detection threshold and sets the CFAR, increases as the signal level rises. High level signals from the turbines raise the average value, raise the detection threshold and subsequently reduce the detection probability. Suppressing data in the cells representing the high level signals contributing to the averaging process reduces the threshold and hence reduces detection losses of aircraft in the vicinity of the wind turbines. Appendix F Filtering Methods describes the technical details of CFAR.

Suppressing data in the affected cells may be implemented by manually constructing a map based on knowledge of the turbine positions. An alternative method would be to automatically feedback the position of the turbines from the track extractor having identified the MTI/MTD residues from the slow plot filter. Implementing the manual method of constructing a map is possibly the simplest and least demanding of the two methods since it would involve modifying the radar signal processor. Implementing the automatic method would involve modifications to the signal processing and the track extractor. The method would be ineffective if the density of turbines raises the level in each cell contributing to the background average.

6.3 High Resolution Clutter Mapping

Clutter maps are incorporated into the Normal Radar channel and, in a radar configured for MTI/MTD, the Ground Clutter Filter. The purpose of the clutter map is to store the average background clutter level in a succession of range/azimuth cells and sense a change of level in response to a moving object. Decreasing the clutter map cell sizes in range increases the number of cells in between the turbines and therefore increases the probability of detecting an aircraft in the gaps.

A reduced clutter map cell size necessarily corresponds to a smaller resolution cell size, consistent with a wider instantaneous bandwidth. Increasing the instantaneous bandwidth affects most parts of the radar sensor. Implementation requires a wider instantaneous bandwidth transmitter, a wider instantaneous bandwidth receiver, signal processing to cope with the faster sampling rates and increased memory. The plot and track extractor would also need to cope with increased data rates and increased volume of data.

6.4 Radar Absorptive Material (RAM)

RAM is used extensively to absorb radiated RF energy. Cladding the wind turbine tower and nacelle with appropriate RAM material could significantly reduce the RCS from the stationary parts of the turbine structure. The technique, already adopted by the military in harsh environments, is likely to provide approximately 20dB reduction in RCS for cladding approximately 15mm thick. The RAM material is unlikely to be maintenance free but considering the military applications, especially those for the navy, should ensure long intervals between maintenance periods. 'Tuned' RAM is likely to provide greater attenuation over narrow bands.

Cladding the blades with RAM is likely to reduce the RCS but is impractical and therefore not considered.

6.5 Shaping the Tower

Shaping the tower so the reflecting surface is not normal to the radar will significantly reduce the RCS. Modelling indicates a tower with 50dBm^2 RCS when normal with a straight line to the radar, reduces to less than 25dBm^2 RCS for a change in aspect angle deviating 0.5° from normal to the vertical plane. Thus designing a tapered tower or positioning the tower so a straight line to the radar deviates from normal by greater than 0.5° will avoid the large RCS indicated by the modelling.

6.6 Plot and Track Filters

Modern plot and track filters now have the processing power to incorporate multiple hypothesis techniques offering algorithms that can easily and quickly form tracks in dense clutter regions whilst maintaining the required false track rate. Many simple track filters have difficulty in forming tracks on moving objects in the presence of clutter. The method of delaying track output on false clutter tracks results in 'seduction' of new plots from moving objects so the track is maintained for a while before fading.

The modern plot and track extractor possibly is the least intrusive of the methods considered to mitigate the affects of wind turbines on target detection since it does not change the performance of the radar but performs filtering on the existing outputs. It is likely that universal plot and track extractors can interface with many radar types, as many connections to the radar processor outputs are already required for general operation. Some simple radar sensors, not incorporating sophisticated processing, will most likely produce copious false alarms but the modern plot and track extractor is considered likely to cope. The plot and track extractor cannot reduce the losses already incurred by the radar signal processing.

Evidence of the effectiveness of this technique is provided in Appendix F where results from actual windfarms are shown.

6.7 Plot or detection suppression areas

Radars not fitted with track extraction processing are dependent upon a form of storage in the display so the operator can see tracks as fading long traces on the display. In areas of dense clutter it might be considered expedient to suppress the plots or detection of objects corresponding to the location of the wind turbines and so reduce the displayed clutter density. Plots corresponding to an aircraft moving over the suppressed clutter regions will also be suppressed but it might increase the probability of 'seeing' the target plots in between the individual turbines. Designation and setting up of the suppression areas would be a manual task performed by the operator.

6.8 Range Azimuth Gating (RAG)

Some radar sensors are designed with RAG maps that enable various functions to be implemented at selected ranges and azimuth sectors. The purpose of the RAG map could be extended to suppress the plots corresponding to the wind turbine clutter regions. Unlike suppression of data in cells for the CFAR case, suppression would be applied to plot data after the background averaging process. Setting up of the RAG map cells could be the same as for suppression of data in cells for the CFAR process, that is, manual set up or automatically from the track extractor.

6.9 Track initiation inhibit

Initiating a track over a wind farm is likely to generate many false tracks thus increasing the false track rate. Inhibiting track initiation in the vicinity of the wind farm enables tracks that have already been created on moving objects to continue over the affected area. Unfortunately the method, although incorporated in old track extractors, suffers with seduction, as the plot from the aircraft can become associated with that of the turbine. The method might be perceived as a short-term solution but with the high risk of breaking tracks and seduction.

6.10 Geometry

The physical geometry of the radar relative to the objects of interest is important when analysing the response of the radar. A significant characteristic of the geometry is the angles of incidence between the turbine axes and the vector from the radar to the turbines since it can affect the ability to detect aircract in the vicinity of the turbines. Additionally the geometry can effect the number of turbines declared erroneously as ‘stationary aircraft’. See Section F.2.1.

6.11 STC

The technique of Sensitivity Time Control (STC) is a method of changing the sensitivity of the radar receiver so that the signal level passed into the radar processing remains reasonably constant with range. It is most useful in reducing the probability of the large magnitude reflections from a wind turbine tower, within the STC range, from amplitude limiting the receiver/signal processing. The method will provide little benefit in reducing the effects from low level returns in the presence of a large reflection from a turbine. The technique is also known as Swept Gain Control (SGC). See Section A.8.1.

6.12 Secondary Radar/IFF Plots

For civil applications the extraneous SSR/IFF reflections are usually small in number and can be displayed without risk after suitable operator training. In extreme cases the SSR/IFF codes returned on the plots may often help in the automatic identification of a reflected return.

6.13 Summary of Mitigation Methods

A summary of the mitigation methods is produced in Table 6.1.

	Function	**Implementation**	**Result**
1	Plot blanking	The plot is blanked in the area of the turbine or group of turbines. The position of the turbine is required to effect the blanking.	Loss of aircraft detection in the blanked areas.
2	Range Azimuth Gating (RAG) map	Programme the RAG map to blank the video output and therefore inhibit the passing of plot data to the plot extractor. Some systems are configured with this capability.	Loss of aircraft detection in the blanked areas.
3	Blanking cells in the background averaging process.	Blank the one or two of the cells, corresponding to the high levels from the turbine, contributing to the background average.	Reduces the average level in the background and therefore reduces the losses in the background averaging process. Only one or two cells may be blanked otherwise the averaging process will not function correctly.
4	MTI processing	MTI filtering is incorporated into many ATC radars.	Processed data representing the magnitude of the reflected energy from the static components of the turbine will be reduced by the MTI processing. Doppler offset frequencies are imposed on the reflection from the moving components of the turbine, such as the blades. The sensor is unable to differentiate between the response from the blades and that from the aircraft.

Table 6.1 Summary of Mitigation Methods

	Function	Implementation	Result
5	MTD processing	MTD filtering is incorporated into some ATC radars. A modification to control the filter blanking would require information on the wind turbine response.	The arguments are similar to those for MTI since the spectrum from the Doppler effect is likely to occupy all the MTD filters. Modifying the MTD configuration to blank the filters containing the responses of the turbine offers the prospect of detecting aircraft in the vicinity of a turbine provided: (1) The signal level is not high enough to cause non-linearity. (2) The Doppler offset frequency resulting from the turbine is less than the first blind speed and is also less than the Doppler offset frequency of the aircraft.
6	Geometry	Positioning of the wind turbines within a wind farm relative to the radar.	Minimising the number of range cells containing responses from wind turbines will improve aircraft detection in the vicinity of the wind farm. For example siting the turbines so that within an antenna azimuth beamwidth the number of range cells occupied with data representing the wind turbines is minimised. See Figures in the Appendix, F3 and F.4.
7	Clutter mapping	Clutter maps are a feature of many ATC radars and may already be effective in improving aircraft detection in the vicinity of turbines.	The background level in the clutter map is an average across a many cells, thus if the aircraft returns a signal greater in level than the background then detection of the aircraft is probable. The method will not be effective if the signal level causes amplitude limiting.

Table 6.1 Summary of Mitigation Methods (contd)

	Function	**Implementation**	**Result**
8	Plot & track extraction	Sophisticated algorithms in conjunction with modern processors provide the basis for an advanced track extractor.	Advanced track extraction although unable to substitute for poor or missing data can base decisions on more data than was possible previously. The techniques increase the visibility of aircraft in a clutter environment.
9	Reduced range cell extent	A major change to the radar involving increased bandwidth, narrower pulse widths and increased sampling rates. Modification more suited to a pulse compression radar.	Reduced range cell extent enables improved inter-clutter visibility, that is the ability to detect in the gaps. Improved detection of aircraft in between the turbines can be expected.
11	RAM cladding to reduce RCS	Radar Absorptive Material is used to absorb electromagnetic energy in the radar frequency bands.	Cladding the stationary parts of the turbine with RAM is expected to reduce the level of reflected energy and therefore in particular situations reduce the potential to cause amplitude limiting. A reduction of 15dB is considered realistic although some maintenance can be expected. Only parts of the turbine that are likely to provide high reflectivity need be clad.

Table 6.1 Summary of Mitigation Methods (contd)

	Function	Implementation	Result
12	Shaping to reduce RCS	Shaping the tower to reduce the reflected energy directed back to the radar.	The greatest proportion of energy returned to the radar occurs normal to the reflecting surface. Shaping the tower and nacelle to cause the reflected energy to be directed away from the radar is expected to reduce the potential for amplitude limiting. Multi-faceted reflectors can also reflect the energy away from the radar. Care should be exercised in choosing the direction of the reflection.
13	STC	Sensitivity Time Control is incorporated into many ATC radars to reduce the potential for amplitude limiting. The sensitivity varies nominally proportional to range to the power of 4.	Within the reduced sensitivity range of the STC clutter levels are reduced, thus the potential to cause amplitude limiting is reduced.
17	Secondary Radar Plots	Secondary radar plots in conjunction with primary plots should provide similar positional information.	Combining primary and secondary plots should improve the track performance. Tracks not substantiated by both radars indicate a probable false track.
18	Automatic Initiation Inhibit Areas	Implemented in older radar systems to inhibit the creation of new tracks in selected areas.	A draconian measure introduced to reduce processor loading and prevent new tracks being formed by such objects as wind turbines. A disadvantage with the method is that a track already formed on an aircraft can be seduced by a wind turbine.

Table 6.1 Summary of Mitigation Methods (contd)

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SECTION 7
COST ESTIMATES

7.1 Scope

Modifying ATC radars to incorporate the facilities discussed in the previous section carries a burden of other activities that must be conducted. In this study a number of approaches to the modifications have been considered. These approaches have sought to assess the tasks to be performed, the risks that have to be borne by the various stakeholders and the time scales that are involved. These approaches have been based on the general process depicted in the DTI's Interim Guidelines document, Reference 20. Appendix G provides more detail regarding the costs.

It has not been possible in this study to define a programme that minimises all risks and simultaneously provides a rapid response to every wind farm application; such an ideal process would have to start before any windfarms had been erected. The UK is well into the development of its wind energy programme with, at the time of writing this report, nearly 1000 turbines installed, so the radar issues must be addressed pragmatically from the current situation.

Nevertheless, the activities that are required have been identified even though an ideal sequence of these activities is not available. This has allowed a cost model to be developed that assesses a number of cost issues:

- The variation in modification complexity. The results of early evaluation of a wind farm application may result in a number of outcomes including outright rejection. For this study it is assumed that, as a consequence, either a simple modification or no modification at all is deemed necessary or a significant modification is required.
- Variation in equipment complexity. Given that a significant modification is required, then there will be variations in equipment designs that result in a variation in modification costs.
- Cost variation with experience. Given that today's level of experience of radars in proximity to wind farms of the size and designs envisaged for the future is very limited, then cost of modifications will initially be high. This reflects the level of risk that is inherent in embarking on a programme where the outcome cannot be fully guaranteed at the outset. As developments proceed of course experience will be gained and the risks of later modification will reduce significantly with time.

Appendix G provides a rationale for a number of cost models and a breakdown of the cost structures. As far as possible, the costs cover activities over the complete scope of the pre-planning and implementation phases pertaining to a radar installation. The figures give an assessment of probable costs but cannot be construed to form a quotation or formal estimate that can be applied to any particular case. As explained in the Appendix, each site will require individual assessment to determine the most cost effective solution to any planning objections and this process will result in cost estimates that are particular to that set of circumstances.

The figures for costs given below are based on the professional experience of the authors and their business associates in assessing the cost models and processes.

7.2 Cost figures

For a modification that requires only changes of setting, minor software changes or no modifications at all, the activities are assessed to cost less than £100k per radar.

For a significant modification that requires changes to hardware and/or software that changes the radar characteristics significantly and therefore requires significant re-qualification by the regulatory authorities then costs per radar are assessed at between £250k and £600k depending on the equipment complexity. These costs are those that would be incurred once significant development and risk reduction had occurred.

For a programme of work that modifies a proportion of the UK ATC radar base over a period of time, and therefore results in risk reduction over a period, then assuming say 30 radars require significant modification then the cumulative costs are assessed to lie between £8M and £19M.

The logic of these costs is depicted in the Figure 7.1.

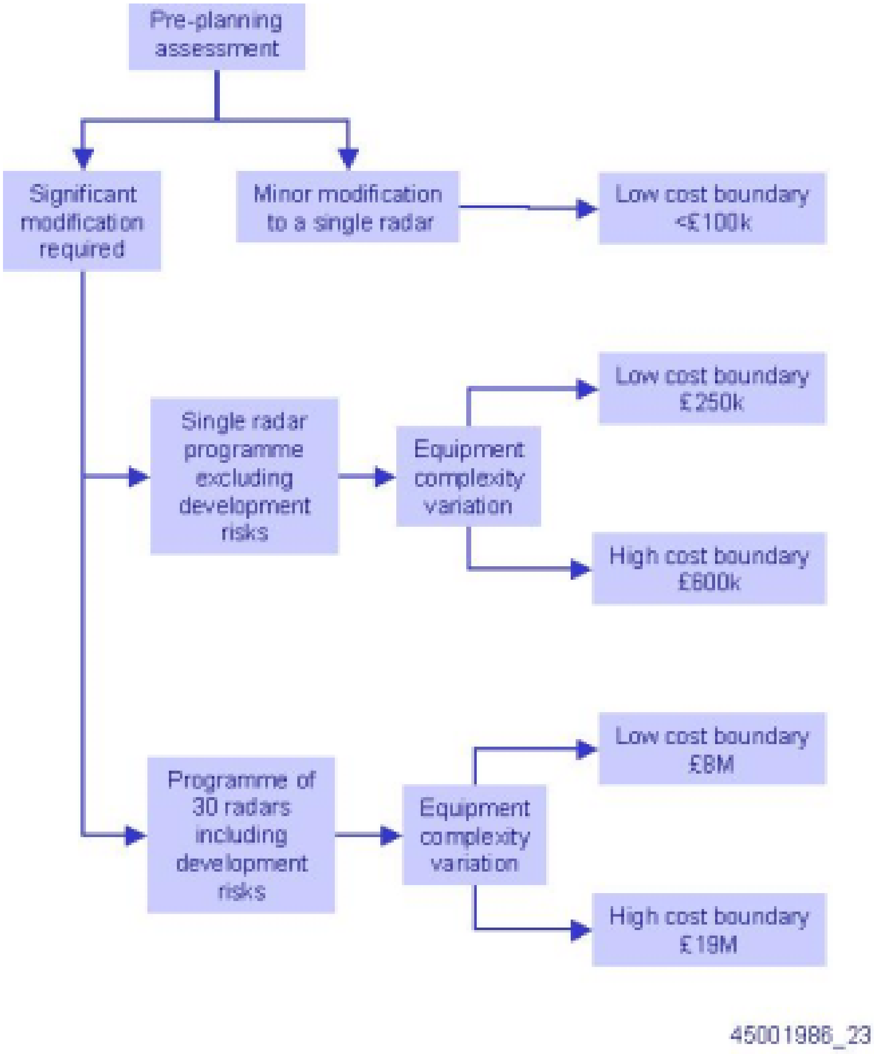

Figure 7.1 Radar Modification Cost Logic and Summary

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SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

This study has indicated the potential for wind turbines to significantly affect the performance of ATC radar. Modelling indicates, in particular circumstances, the potential for signals echoed from the massive turbine tower and blades to overload the radar receiver. Furthermore the echoes from the moving blades can appear to some radars equipped with moving target processing as moving objects.

Potentially there are several effects that fall into two main classes when a turbine or a farm of turbines is visible to radar:

- Reports of false targets (aircraft) to the operator
- Probability of detecting aircraft is degraded

8.1.1 Radar characteristics of turbines

Modelling

Investigations revealed the many different types of turbine and considerable variations in size and speed of the rotating blades. Analysis has therefore been limited to the high power types of turbine that might be installed in the future since it appears they will be larger than many types belonging to the present generation. Data was acquired from many sources including the Internet and a turbine manufacturer. It is likely any further study will require more information, especially relating to the dynamics of the turbines.

Only simple modelling of the component parts to estimate the total RCS of a generic turbine was considered necessary since evolving a more complicated representation would have been time consuming and would not have provided any useful information. Providing a precision model would have required definition of internal components, both in the blades and in the nacelle. Furthermore, accurate definitions of materials, precise physical measurements of all components and effects due to stress from the wind are just a few of the elements that would facilitate an accurate model. Experience of precision modelling has shown that computer power and time to execute for such an activity would be massive. Understandably some manufacturers appeared reluctant to divulge particular details of the turbine design because of IPR issues.

Corresponding to both L band and S band operation, modelled results indicated a peak RCS of greater than $10^5 m^2$ for the turbine tower along a line at right angles to the side of the tower. Changing the angle of incidence by greater than 0.5° results in an RCS of approximately $10^3 m^2$ for the L band case and approximately $10^2 m^2$ for the S band case. Modelling indicates that the RCS is sensitive to elevation angle of incidence thus, the corollary is, avoid positioning the radar on a line at right angle to the side of the tower. If the condition cannot be avoided with a cylindrical tower then shaping the tower as a cone achieves a change in reflection angle.

The RCS of a three-bladed turbine has been modelled as a function of azimuth around the tower for three angular positions of the turbine and two angles of blade pitch. RCS results representing the L band response are mostly invariant with azimuth angle and are in the order of 30dB m^2 although a few peaks exceed 50dB m^2. RCS results representing the S band response vary with azimuth angle, mostly between 10dB m^2 and 30dB m^2 although a few peaks achieve 60dB m^2. The conclusion is that, except for the peaks, the RCS of the turbine is mostly less at S band than at L band. Modelling the responses for two blade pitch angles indicated little change to the RCS.

Measured data from the Swaffham wind turbine gathered by QinetiQ as part of a DTI Study (Reference 17) indicate a spectrum that is dependent on the attitude of the turbine with respect to the measuring equipment. The power spectrum generated at right angle to the axis of rotation occupies a much greater bandwidth than the spectrum generated in line with the axis of rotation. The difference in spectral power density resulting from vertical and horizontal polarisation is small. Most noticeable in the case of measuring at right angle to the axis of rotation is the short duration over which the frequency deviates, thus the probability of intercepting this excursion with a pulsed Doppler radar is small.

8.1.2 Effects on radar performance

Data generated from modelling indicates that large turbine towers, at the operational frequency of the radar, can present an RCS in the order of $10^6 m^2$. Assuming a typical requirement of ATC radar is to detect a $1m^2$ RCS aircraft then the system dynamic range would need to exceed 60dB. The problem of the tower presenting a large RCS to the radar is exacerbated as the number of turbines within the radar beam and each range cell increases. In the case of MTI/MTD processing, requiring linear operation, achieving the indicated large dynamic range is considered difficult with current technology.

A large echo from a wind turbine, causing the radar receiver to amplitude limit, is likely to reduce the probability of detecting an aircraft if the echoes from both objects are received coincidentally. Desensitisation reduces as the range separation of the two echoes increases although there is a probability of generating false targets. Neither a radar sensor based on a self-oscillating transmitter nor pulse compression is immune to the problem although the pulse compression radar is likely to be affected over a greater separation of the echoes in time or range. Linear active circuits in the radar receiver subjected to amplitude limiting are unlikely to recover quickly.

The Normal Radar channel is not configured with Doppler filter processing thus data representing both moving and non-moving objects are present so wind turbines manifest as clutter, possibly large in magnitude. Clutter mapping is incorporated into most ATC radar sensors as a means of detecting moving objects based on the signal level changing over the clutter region. Modelling indicates, under particular conditions, significant variations in RCS as the turbine rotates which are likely to be detected.

The background averager responds to large signal levels, albeit in just a single cell of the averaging process, therefore a higher background level increases the detection threshold and reduces the detection probability. RCS modelling indicates the received echoes can be large and therefore cause desensitisation.

The measured power spectrum, centred on zero offset frequency, indicates continuous occupancy up to the frequencies corresponding to the blade tip velocities. Since the greatest magnitude of all the MTD filters is selected for detection and will probably contain the turbine response, then detection of a small target is improbable. The radar positioned at right angles to the axis of rotation presents the widest spectrum and exceeds the radar first blind speed, however positioning the radar in line with the axis of rotation reduces the spectral width to below the first blind speed. If some of the low order MTD filters, containing the turbine spectral data were to be blanked (or alternatively select the appropriate filters for detection) then it appears possible to detect an aircraft in the higher order filters not occupied by the turbine spectral data.

Simple radars not incorporating a plot filter are likely to present the operator with a confused radar picture in response to an aircraft flying over a wind farm. An improved picture undoubtedly results from plot filter processing although older plot filter designs are likely to create abundant false or discontinuous tracks. Furthermore, plots generated from two adjacent turbines received on two separate scans can create false tracks indicating high velocity.

8.1.3 Mitigation of effects

Designing a cost effective radar receiver to linearly process signals over the range of levels identified in the report is considered unlikely. Reducing the RCS of the turbine is perceived as the most effective solution. Cladding the tower and nacelle in RAM is a possible method although some maintenance might be required. Shaping the tower and nacelle housing (if fabricated with reflective material) to reflect the electromagnetic energy away from the radar is an alternative method but can only be implemented if this does not create a problem for any other local systems (radars, navigation aids, communications, TV, etc). Siting the wind turbine so the peak of the returned energy is not directed at the radar provides another method.

Positioning of multiple turbines can affect the radar performance. The example presented in the study is based on positioning each turbine on a rectangular lattice although the actual positions may be a compromise with other requirements. The aim is to minimise the number of processing cells containing data representing returns from the turbines.

Increased processing losses as a consequence of the increased background level can be mitigated by excluding data in the cells representing the high level signals. Setting up could be implemented statically or under control of the plot filter.

As in the case of the background averaging process, suppression of data in the clutter map cells representing returns from the turbine can reduce the probability of generating false plots.

De-sensitisation of the radar receiver to decrease the level of returns from the turbines is a method that can reduce the probability of limiting in the receiver. The technique can only be applied to sensors with an attenuator that precedes the stages likely to limit. De-sensitisation as implied, reduces target detection probability.

A reduced transmitted pulse width, consistent with a smaller range cell size, reduces the effect of aggregating signal magnitudes returned from multiple turbines. It also provides additional cells or 'gaps' in between the turbine returns that can be occupied by returns from aircraft. Reducing the range cell size in existing radar is a major modification since the transmitter, receiver, signal processing and plot extractors are all affected. This supposes that the system can support the increased bandwidth.

Plot and track extraction can help to limit many unwanted effects of wind turbines and will seek to create as few false tracks from the turbines as possible, in particular plots emanating from adjacent turbines in a wind farm. Ideally the process is intended to maintain air tracks across a wind farm without deletion or seduction and minimise the loss of tracks in areas behind a wind farm.

The study has considered how the wind farm effects upon the radar might be overcome. A low loss Plot Filter using modern track maintenance and filtering methods, offers a process to mitigate some of the effects although it will be necessary to counter other aspects of the problem such as limiting. There are many radar types and configurations, various sizes and designs of wind turbines, positioning the turbines within the wind farms, statistics of the weather conditions that it is believed impossible to find a universal solution that will negate all wind farm effects in all conditions.

Additional work is required to further study the effects and investigate the performance improvements offered by some of the methods considered in this study.

8.2 Recommendations

The study has addressed many features of wind turbines that are likely to affect radar performance. Further work is required to quantify the magnitude of the problem nationally and propose means to mitigate the problem. A clear solution has been identified for removing unwanted detections but various features of the turbine, radar and geographical location need to be considered as part of the design and deployment strategy.

Current deployment and future planning of wind turbines occupy two distinct time frames thus the recommendations are:

- Decide how the current interference can be mitigated.
- Establish a guide for future design and installation of both the turbines and radar.

8.2.1 Current deployment

Practical measurements on the various radar sensors will assist in determining the magnitude of the interference problem. It is essential that the conditions associated with the measurements be recorded in detail as it is indicated by the study findings that minor features of the scenario can significantly affect radar performance. Geographical location of all items in the scenario is crucial to analysing the effects on radar performance therefore precise positions, including relative heights, of the turbines and radar will need to be known.   Much of the content in this report is based on radar theory, which although informative, is not the actual performance in the field. It is therefore recommended that a comprehensive set of trials be conducted at chosen sites to ascertain the effects on radar performance. The trials would be organised to indicate such effects as losses due to background averaging, suppression of permanent echoes by the MTI, amplitude limiting, erroneous target detection, interception with the turbine blades and actual detection of aircraft. Details of the wind turbine type, operational conditions and geometry in addition to the practical results are necessary to evaluate the effects upon the trials results. Trials of this nature would be large and need to be defined as part of a separate study since each scenario is likely to be unique, particularly as nation-wide there are various wind turbines and various radar sensors.

Many features associated with the wind turbine interference problem have been considered although it has been in general terms. Since the study has indicated which parts of the turbine structure might affect the radar performance then it is recommended that the particular relevant topics be studied in greater detail.

More detail is required regarding constructional detail of the wind turbine since there are various features affecting radar performance that, at present, cannot be satisfactorily represented by modelling, in particular the nacelle. The blade type investigated during the study is germane to a particular manufacturer and is not fitted universally. It is therefore recommended that all manufacturers be contacted to understand the differences between the various turbines and possibly assist with providing more information for further modelling.

There are various proposals included in the study, two of which could be implemented in the short term as a trial. Cladding the tower of a suitably located wind turbine with RAM material is recommended to establish, by measurement, the reduction in RCS and if possible assess the effects on a suitably located radar. Additionally it is recommended that a modern, advanced plot and track extractor, of the type described in the report, be fitted to an appropriate radar sensor suffering with the effects of a wind turbine to assess performance improvements.

The most significant improvement to the radar picture is offered by the addition of the advanced plot and track extractor. Assuming successful trials it is recommended that advanced plot and track extractors be fitted to appropriate radars. Other proposed modifications to the radar include reducing processing losses by suppressing data in the background averager cells that represent returns from the turbines. Suppressing data in affected cells of the clutter maps is recommended since it assists with reducing false plots.

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SECTION 9

REFERENCES AND ACKNOWLEDGEMENTS

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The Renewable Energy Helpline – tel 01235 432450, email NRE-enquiry@aeat.co.uk, address: B329, AEAT, Harwell, Didcot.

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SECTION 10

GLOSSARY

Abbreviations

ACP	Azimuth Change Pulse
ACR	Airfield Control Radar provides short range ATC cover for some airports.
ADC	Analogue to Digital Converter
AMS	Alenia Marconi Systems Limited
AMTD	Adaptive Moving Target Detector
AMTI	Area Moving Target Indicator
ARP	Azimuth Reference Pulse
ASDE	Airport Surface Detection Equipment used to control the movements of aircraft on the ground and to detect airport intrusions.
ATC	Air Traffic Control is the generic term for controlling the movements of all airborne traffic.
AWEA	American Wind Energy Association
Az	Azimuth
BWEA	British Wind Energy Association
CAA	Civil Aviation Authority
CAD	Computer Aided Design
CF	Clutter Filter
CFAR	Constant False Alarm Rate
CP	Circular Polarisation
dB	Decibel – a power ratio
DME	Distance Measuring Equipment An airborne element of some MLS systems
DTI	Department of Trade and Industry
El	Elevation

EREC	Energy Efficiency and Renewable Energy Clearinghouse (the U.S. Department of Energy)
EWEA	European Wind Energy Association
FM	Frequency Modulation
GCA	Ground Controlled Approach is the technique for talking down, through the use of both surveillance and precision approach radar, an aircraft during its approach so as to place it in a position for landing.
GE	General Electric Company
GRP	Glass Reinforced Plastic
HSA	Hollandse Signaal Apparaten (now Thales Netherlands)
HSA/TST	Hollandse Signaal Apparaten/Telefunken System Technik
Hz	Hertz – measure of frequency in cycles per second
I	In phase signal
IEA	International Energy Agency
IFF	Identification Friend or Foe
IPR	Intellectual Property Rights
ILS	Instrument Landing System
JAR	Joint Aviation Requirements
JAR –FCL	Joint Aviation Requirements – Flight Crew Licensing
LNA	Low Noise Amplifier
MLS	Microwave landing system supplies glide path information to aircraft for instrument landing. The ground element is a transmitter only
MTD	Moving Target Detector
MTI	Moving Target Indicator
mrad	Milli-Radian
MW	Mega Watt
NATS	National Air Traffic Services

NR	Normal Radar
NRE	Non-recurring Expenditure
PAR	Precision Approach Radars used for the ground control of final approach in emergencies. Used exclusively by the military.
PE	Permanent Echo
PFA	Probability of False Alarm
PPI	Plan Position Indicator
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
PSD	Phase Sensitive Detectors
Q	Quadrature Phase Signal
RAF	Royal Air Force
RAG	Range/Azimuth Gate (a method of adapting radar processing to the environment that surrounds the radar).
RAM	Radar Absorptive Material
RCS	Radar Cross-Section
RES	Renewable Energy Systems Limited
RF	Radio Frequency
RSR	En-Route surveillance radar
S/N	Signal to Noise ratio
SGC	Swept Gain Control
SRG	Safety Regulation Group (CAA)
SSR	Secondary Surveillance Radar
STC	Sensitivity Time Control
T/R	Transmit/Receive (used to define position of radar in the turbine modelling)
TAR	Terminal Area Radar
TMA	Terminal Manoeuvre Area

TWT	Travelling Wave Tube
VOR	VHF Omni directional Range. Used for aircraft navigation. Beacon giving bearing information only.
WEG	Wind Energy Group

Definitions

S-band	The frequency band from 2GHz to 4GHz. This is divided for the purposes of spectrum management into various sub-bands. The frequency band 2700-2900 MHz houses the airfield surveillance and air traffic control radars of civil aviation, military, MoD PE airfields and naval radars. Maritime, air traffic control and range safety radars operate in the frequency band 2900 - 3100 MHz. The frequency band 3100-3400 MHz is used for short-range air and ship defence systems and long range air defence and airborne radars. The frequency band 2300-2450 MHz is allocated for radar on a secondary basis for UK MoD. In the band 3400-3600 MHz there are some frequencies for airborne and naval radars and for radar development.
Ku-band	The frequency band 12-18 GHz. Portions of the bands are designated for communications, radar, intruder surveillance and television.
L-band	The frequency band from 1GHz to 2GHZ. Within this band the range 960-1215 MHz is designated globally for aeronautical radio navigation systems including primary radar. The frequency band 1215 to 1350 MHz accommodates surveillance radars primarily for maritime and air defence.

dBm^2	Radar cross section in Decibels w.r.t. one square meter. The radar cross section figure (in square metres) expressed on the decibel scale. The decibel value is calculated as: dBm^2 = 10*log$_{10}$(RCS in square metres/one square metre) To put a scale on this: 60 dBm^2 = 1 million square metres 20 dBm^2 = 100 square metres 10 dBm^2 = 10 square metres 0 dBm^2 = 1 square metre -10 dBm^2 = 0.1 square metres -20dB m^2 = 0.01 square metres -40dBm^2= 0.0001 square metres
Instrumented Range	The range from the radar that equates to the time between transmitted pulses from the radar. This is the theoretical maximum range at which targets can be reported by the radar.
Coning angle	The blades of a turbine rotor do not necessarily rotate in a flat plane. Sometimes the design sets the blades at a slight angle forward from the flat plane so they rotate in a shallow cone. The coning angle is the angle of the blades w.r.t the plane normal to the axis of rotation.
C-band	The frequency band from 4GHz to 8GHz. Weather radars operate in the region of 5600 MHz. Military tactical radars use the frequency band 5250-5850 MHz.
X-band	The frequency band from 8 GHz to 12.5 GHz
dB	dB decibel: used to express a ratio eg ratio of two powers: 10.Log$_{10}$(P2/P1)
dBA	A weighted sound pressure level expressed as : 20.Log$_{10}$(P_m/P_{ref}) where P_m is the RMS measured pressure and P_{ref} is the reference pressure defined as 20µ Pascals.
E field	Electric field
H field	Magnetic field

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