

**WIND TURBINES AND RADAR:  
OPERATIONAL EXPERIENCE AND MITIGATION MEASURES**

**Report to a consortium of wind energy companies**

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## **1. INTRODUCTION**

This report presents results from the study commissioned by Natural Power Consultants Ltd on behalf of a consortium of wind energy companies on 16 March 2001, on the generic issues relating to the impact of wind turbines on radar and air traffic management, and mitigation measures to address those impacts.

The focus of this report is collation of information on the practical experience of air traffic service providers of the effects of wind turbines on radar, and the operational consequences thereof. Until now, stated safeguarding policy, particularly in the Ministry of Defence, has been driven mainly by engineering analysis which has focused on the theoretical probability of wind turbines appearing on radar. However little work has been carried out on the significance, from the perspective of air traffic management, of any visible effects on radar.

This report identifies locations both in the UK and abroad where wind turbines are line of sight to radars, and presents evidence on the nature of any effects of radar and their significance for the effectiveness and safety of air traffic control.

The project workscope is reproduced at Appendix A. A list of consultees is reproduced at Appendix B.

## 2. TYPES AND FUNCTIONS OF AIR TRAFFIC RADAR

Air traffic control radar is of two types. Primary surveillance radar equipment sends out pulses of electromagnetic energy which will reflect off objects in their path. The radar's receiver antenna detects the returning 'echoes' and these are displayed on the radar screen. The time taken for the pulse to travel out to the target and back gives an indication of the range of the object from the radar, while the antenna's orientation in azimuth (in the horizontal plane) indicates the direction of the object from the radar. Primary radar has no intrinsic means of differentiating one type of object from another; its energy will bounce off any object in its path.

Primary surveillance radar for air traffic control has no means of determining the height of any object. As the radar antenna sweeps round continuously through 360°, it is scanning a large sector of airspace in the vertical plane, typically from 0° elevation up to 40°. Any objects which are over the same location laterally but are separated vertically will appear in the same place on the radar screen, which is a 2-D display.<sup>1</sup> To determine the height of any aircraft appearing on their radar, controllers must either ask the pilot to report the height of the aircraft, and/or use information derived from secondary surveillance radar.

Secondary surveillance radar (SSR) is the second type of radar equipment used for air traffic control. Like primary radar, SSR relies on an antenna rotating continuously through 360°. However the radar does not transmit raw pulses of energy; it transmits an interrogation signal. This triggers a response signal from equipment known as a transponder in the aircraft. The response signal contains a four-digit code which is set by the pilot, and in most cases also contains the height of the aircraft. The returned transponder signal is received at the SSR antenna, decoded, and the four-figure code and height are presented on the radar screen next to the aircraft's location. This enables controllers to positively identify radar returns on their screens and (after verbal confirmation from the pilot) to confirm their height. In the UK, all aircraft flying at or above 10,000 feet, and all aircraft flying on instruments in controlled airspace, must carry a transponder. All airliners and military aircraft carry SSR transponders. Some light aircraft do not. Aircraft fitted with transponders may not have them switched on, in which case they will not be visible to SSR.

Most air traffic control radar units are equipped with both primary and secondary radar. The SSR antenna is often located on top of the primary radar antenna, the two rotating together. Some air traffic control units have SSR data fed to them from a remote site by landline or radio link. In some cases - for example over south west England and north west Scotland - radar services to en route traffic are provided using SSR only, without primary radar.

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<sup>1</sup> Modern air defence radars are able to differentiate between targets vertically by using antennae which are segmented, with each antenna segment scanning a separate elevation angle.

Radar has a number of inherent technical limits to its performance. These are outlined in a CAA circular:

"The performance of even the most modern radars is rarely perfect. For example, returns from small, slow-moving aircraft such as hang gliders, microlights etc may be suppressed by electronic circuits which cancel unwanted radar returns from road traffic, weather and terrain. Even when displayed, radar returns from small or slow-moving aircraft are occasionally indistinguishable from certain non-aircraft returns. In the worst case, it may be impossible for the controller to determine conclusively that a transitory radar return is that of an aircraft. Hence, controllers may not always be aware of all potential conflicts, and may be unable to pass avoiding action and/or traffic information when an aircraft to which they are providing a radar service is in the vicinity of a small or slow-moving aircraft."<sup>2</sup>

### *Functions*

Radar performs two principal functions in air traffic control. Aerodrome surveillance radar is used to provide approach control services to aircraft in the vicinity of an airport. This may include vectoring aircraft to the final approach for landing, providing radar services to departing aircraft, and providing a service to aircraft in transit through the area. In the UK, aerodrome surveillance radar is approved to a maximum range of 42.5nm from the airfield. Aerodrome surveillance radars typically operate in the 10cm waveband.

En route radars, which in the UK are all operated by National Air Traffic Services (NATS), are used to control or provide radar services to traffic in transit. This includes commercial airliners and other traffic flying in controlled airspace, and military traffic. Most en route radars operate in the 23cm waveband - a lower frequency than aerodrome surveillance radars - since this gives the radar longer range. Some NATS radars - such as those at Glasgow, Aberdeen, Belfast and Sumburgh - perform a dual function of aerodrome surveillance and en route.

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<sup>2</sup> UK Aeronautical Circular 2/2001 (Yellow 33), 11 January 2001: *Services to Aircraft Outside Controlled Airspace*, para.4.5.1.

### 3. AIR TRAFFIC RADAR SERVICES

An outline of the policies, standards and procedures for provision of air traffic radar services in the UK is necessary in order to understand the basis for expressed concerns about the impact of wind turbines on radar, and the feasibility of any mitigation measures.

#### *Air traffic control services in the UK*

Article 88 of the Air Navigation Order (ANO) 2000 requires that civil air traffic control (ATC) services in the UK are provided only under the terms of an approval granted by the Civil Aviation Authority (CAA). Article 89 of the ANO stipulates that such air traffic services may only be provided in accordance with standards and procedures specified in a CAA-approved manual of air traffic services. The UK regulatory regime for civilian air traffic control is goal-setting in nature - air traffic service (ATS) providers are responsible for making their own decisions on the services they provide and how they will meet legal obligations and safety standards. The CAA then assesses whether the ATS provider's proposals meet safety objectives. If the objectives are met the CAA grants approval. Continuing approval is achieved through auditing and inspection, provided in the case of aerodrome radars through three CAA Safety Regulation Group (SRG) regional offices across the UK.

Generic national ATC standards and procedures are set out in the Manual of Air Traffic Services Part 1 (MATS Part 1). This document provides both mandatory instructions and discretionary guidance to controllers and additionally states "(n)othing in this Manual prevents controllers from using their own discretion and initiative in any particular circumstance."<sup>3</sup>

The standards and procedures applying to particular air traffic control units are set out in a separate MATS Part 2 for each unit. These also require CAA approval.

For military air traffic control services in the UK, the standards and procedures are set out in a document known as JSP 318A.

MATS Part 1, Section 1, Chapter 3, specifies the minimum standards for separation distances between aircraft to be applied by air traffic controllers. These can be defined as horizontal distances, vertical distances, or time periods.

Controllers providing a radar service will apply minimum separation standards either by ensuring that aircraft returns on the radar display are the specified minimum horizontal distance apart, or by ensuring that aircraft are separated vertically by the required minimum distance.

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<sup>3</sup> Civil Aviation Authority, *Manual of Air Traffic Services, Part 1*, CAP 493 (CAA, London, 1989, as amended), p.1-1.

For the purposes of this report, the required minimum separation standards can be summarised as those applying in controlled airspace (CAS) and those applying in uncontrolled airspace.

Controlled airspace exists around major airports and in 'airways' along the main air traffic routes. In almost all CAS in the UK, aircraft are not permitted to enter that airspace unless they have received an air traffic control clearance. In general, controllers are permitted to assume that any radar return appearing within the lateral confines of their airspace, which does not correspond to the position of an aircraft which has received a clearance, is not an aircraft.<sup>4</sup> They will then not be required to provide separation between the unknown return and any aircraft to which they are providing a service. In most controlled airspace in the vicinity of airports in the UK, the minimum separation between aircraft is 3nm horizontally or 1000ft vertically. These minima are lower than in uncontrolled airspace because controlled airspace is a 'known traffic environment', where the intentions of all traffic are known and therefore the movements of aircraft are predictable. Radar equipment must also meet specified performance standards in order to support 3nm separation.

In uncontrolled airspace, because unknown aircraft may be present, including some which are invisible on radar due to their size, shape and/or construction materials, minimum separation distances are normally larger. Where aircraft are being provided with a Radar Advisory Service in uncontrolled airspace (see below), controllers will seek to maintain separation of 5nm horizontally or 3000ft vertically against non-participating traffic (aircraft which are not being provided with an air traffic service by the same unit).

These separation standards are minima and can be increased at the request of a pilot, when a controller considers it necessary, or at the direction of the CAA. The standards can also be reduced in some circumstances. This requires CAA approval and the reduced minima must be published in the MATS Part 2 for the unit concerned.

Horizontal minima are measured between the centres of the primary returns and, where the returns are raw radar data (not processed), they must not touch or overlap.

When primary radar data are supplied, the horizontal separation must be measured using those primary data. However MATS Part 1 does permit SSR data to be used alone as a basis for providing horizontal separation between aircraft, in the following circumstances:

- "(i) Where this use has been approved by the Authority.
- (ii) To overcome temporary deficiencies within primary radar cover, such as fading or clutter, the secondary return only of one aircraft may be used to provide separation from the primary or

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<sup>4</sup> Or, in cases where the CAS does not extend all the way to ground level, the radar return can be assumed to be an aircraft flying below the base of the CAS.

secondary return of another aircraft provided the primary and secondary radar displays are correctly aligned."<sup>5</sup>

SSR-only separation cannot, however, be used "if a controller has any doubt about the accuracy of the position of radar returns due to equipment malfunction, reflections or any other reason."

The standards laid down by the CAA Safety Regulation Group (SRG) in CAP 670 *Air Traffic Services Safety Requirements* specify that for a radar to be approved to provide 3nm separation between aircraft, it must have a 95% or greater probability of resolving (i.e. distinguishing between) two targets which are 1nm apart over the whole of the radar's required azimuth and range. To provide 5nm separation, it must be able to resolve two targets 3nm apart.

#### *Types of radar service*

There are three types of radar service available to air traffic - radar control, radar advisory and radar information.

A radar control service applies only in controlled airspace. Under a radar control service, controllers issue heading and altitude instructions to pilots which must be obeyed by the pilots. These instructions are designed to ensure that standard vertical or horizontal separation is maintained between all aircraft. In normal circumstances, unidentified or unknown air traffic can be disregarded in this airspace since it is a 'known traffic environment' where all aircraft in the controlled airspace are in contact with, or known to, the controller. In these circumstances, it can be assumed that unidentified radar returns are either not aircraft, or are aircraft operating outside (e.g. below the base of) the controlled airspace.

A Radar Advisory Service (RAS) is available to aircraft flying under the Instrument Flight Rules (IFR)<sup>6</sup> in uncontrolled airspace. Under a RAS, controllers pass information on other traffic to pilots receiving the service, and also advice on headings and/or altitudes to fly to maintain the standard 5nm or 3000ft separation from the other traffic. "However, it is recognised that in the event of the sudden appearance of unknown traffic, and when unknown aircraft make unpredictable changes in flight path, it is not always possible to achieve these minima."<sup>7</sup>

A Radar Information Service (RIS) is available to traffic flying under IFR or VFR (Visual Flight Rules). Under a RIS, controllers will pass information on the position and altitude of other traffic but will not issue advice on headings or altitudes to fly to avoid conflict. The crew of the aircraft retain responsibility for separation from the other traffic.

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<sup>5</sup> MATS Part 1, p.1-26.

<sup>6</sup> IFR flights can fly in all types of controlled airspace and are separated from other traffic. VFR flights separate themselves from other traffic by 'seeing and avoiding'.

<sup>7</sup> MATS Part 1, p.1-41.

RAS and RIS may be limited by controllers when they judge that they cannot meet the primary requirements of the service. MATS Part 1 specifies that the radar service should be limited when:

- "(a) The aircraft is operating within 10 miles of:
  - (i) the edge of the radar display.
  - (ii) weather clutter, or
  - (iii) permanent echoes.
- (b) The aircraft is operating in an area of high traffic density.
- (c) The aircraft is operating near to the limits of solid radar cover, or
- (d) The service is being provided using secondary radar only."<sup>8</sup>

Radar services to air traffic outside controlled airspace were reviewed in 1997 with the aim of ensuring that the standard of service provided was "broadly identical...regardless of whether the unit providing the service was civil or military."<sup>9</sup> While some differences still exist between civil and military ATC practice, the standards and procedures relating to the provision of LARS are common to civil and military units. According to HQ RAF Strike Command, RAF units are no more or less likely to limit the radar service being provided to traffic in the presence of radar clutter than their civil counterparts.

Following some confusion about the status of a limited radar service, the CAA issued supplementary advice in 2000 which states: "Limiting a service should not be viewed as a failure to provide the desired service but a useful and sensible way for a controller to indicate to a pilot that the full service cannot be provided. However, the controller is still willing to offer assistance to fulfil the primary objectives of the service."<sup>10</sup>

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<sup>8</sup> MATS Part 1, p.1-42.

<sup>9</sup> MATS Part 1, Supplementary Instruction 4/00.

<sup>10</sup> MATS Part 1, Supplementary Instruction 4/00.

#### 4. DISCRIMINATING AIRCRAFT FROM OTHER RADAR RETURNS

The pulsed electromagnetic energy transmitted by radar will reflect off a wide variety of objects in its path. The size, shape, orientation and materials of the object will determine how much of the energy is absorbed, how much is reflected and in what directions it is reflected.

Objects which are moving will cause a shift in the frequency of the returned radio waves - an increased frequency for movement towards the radar, a reduced frequency for movement away from the radar. This is known as 'Doppler shift'. Moving Target Indicator (MTI) processing removes from the radar screen any returned pulses which either have the same frequency as the transmitted pulse (indicating no movement) or are within a specified range of Doppler shift, corresponding to a range of speeds. These thresholds may be set to eliminate a variety of unwanted moving targets, such as rain and other precipitation, trees, the surface of the sea, and road traffic.

MTI processing is based on detecting and measuring the *radial* velocity of a target, i.e. the component of its velocity directed towards or away from the radar. A target which is travelling tangentially to the radar will have zero radial velocity and will therefore be detected as a stationary target and removed by the MTI processor. Aircraft flying tracks diagonal to the radar may only have radial velocities of a few tens of knots, which may be within the threshold speed set to eliminate road traffic, leading again to the elimination of a genuine target.

Further details of techniques for mitigating radar clutter are outlined in section 7 below.

##### *Precipitation*

Returns from weather regularly cause clutter on radar. Areas of rain and other forms of precipitation may be visible, particularly to radars operating at higher frequencies since their waves will reflect more readily off objects as small as a raindrop. Weather clutter will typically cover an area of several miles corresponding to the areas where rain is falling, and may be severe enough to prevent detection of aircraft within the area of clutter. Aircraft - and wind turbines - usually appear as more clearly-defined point targets.

Air traffic radar controllers regularly vector traffic around weather clutter in order to maintain the visibility of the aircraft under their control and to ensure separation from any traffic which may be hidden by the clutter.

Older radars were generally more susceptible to weather clutter. The ACR430, for example, which was in use at a number of UK civil airfields, operated in the 3cm waveband, a higher frequency than most current aerodrome surveillance radars, and was highly vulnerable to weather clutter. In radars of this type, reducing the equipment's susceptibility to displaying areas of precipitation by turning down the gain would often result in aircraft returns being lost in addition to the weather clutter. In these circumstances, controllers would limit the radar service provided, as outlined above. More

modern radars such as the Watchman have improved ability to reduce the effects of weather, but measures taken to remove weather returns from the screen will generally also reduce the radar's ability to detect and track aircraft targets within the area of precipitation.

Radar detection of precipitation is increasingly used for weather reporting and forecasting. In the USA, a network of dedicated radars is used for this purpose. In addition, most modern air traffic control primary surveillance radars developed to US Federal Aviation Administration (FAA) specifications have sophisticated digital signal processing which allows them to detect weather through one or more channels while simultaneously but separately displaying aircraft, with no weather clutter, through other channels.

In the UK, the Met Office has a network of dedicated Plessey 45C rainfall detection radars. These operate at frequencies approximately twice as high as typical air surveillance radars. Met Office radars are generally located on hill tops and are oriented so that the lower part of the antenna beam is at 0° elevation, thus any obstruction at a lower height than the antenna will not be illuminated.

#### *Birds*

Birds can have a radar cross-section of around 0.01 square metre, or approximately one hundredth of the radar cross-section of a small light aircraft. However birds are detectable on radar, particularly when they are travelling in flocks. Their radar cross-section is largest in S-band, the frequency range used most commonly by aerodrome surveillance radars. Flapping wings can create a Doppler shift in the returned signal and can even be analysed in order to determine which species of bird is being detected.

#### *Permanent echoes*

Features such as prominent buildings, hilltops, masts and towers may be constantly visible on the radar screen and identifiable as a particular feature because of their known and static location. These 'permanent echoes' (PEs) will normally be filtered out by MTI processing. However PEs also provide controllers and engineers with a means of calibrating and monitoring the performance of the radar. CAP 670 requires radar controllers or engineers to identify at least three PEs, separated by at least 60° in azimuth, to check range and bearing error on analogue primary radars.<sup>11</sup>

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<sup>11</sup> CAA, *Air Traffic Services System Requirements*, CAP 670, Part C, Section 3, para 16.

## 5. WIND TURBINE RETURNS ON RADAR

Rotating wind turbine blades can impart a Doppler shift to any radar energy reflecting off the blades. The radar's MTI processor may - depending on the thresholds set in the processor - detect this as a non-static target and therefore display it as a return on the radar screen. Variation in the wind direction at the turbine, the precise position of the blade in its rotation as the radar beam illuminates it, the pitch of the blade and other factors may cause the amplitude and size of the return to fluctuate from one antenna rotation to another. At sites with single turbines, any radar return from the rotating turbine blades will stay in one location on the screen. However at sites with more than one turbine, the radar may illuminate a blade or blades from one turbine on one antenna sweep, then illuminate the blades of a different turbine on the next sweep. This can create the appearance on the radar screen of returns moving about within the area of the wind farm over time, sometimes described as a "twinkling" appearance. The extent to which this will happen will depend on, amongst other factors, the radar's range and azimuth resolution - the minimum distance between objects which the radar can detect.

During consultations for this study, several controllers referred to wind turbine returns as being "treated as" or "like" permanent echoes. In these cases, the returns were either static, or shifting on the radar screen by a small enough distance to be considered as remaining in one location. As noted above, regulatory requirements dictate that primary radar displays must have at least three PEs visible on screen in order to provide a means for controllers and engineers to monitor the range and bearing accuracy of the radar. The ability of wind turbines to perform this role will depend on the extent to which the turbine returns are static and consistently visible. This in turn will be dependent on several factors including the number of turbines, their azimuth extent, their range from the radar, and the effects of wind direction and speed on turbine visibility.

### *Airspace*

Wind turbine returns on radar have a much more significant effect when the turbines are located within uncontrolled airspace than when they are situated within or underneath controlled airspace. This is because unknown returns appearing in or underneath controlled airspace can be assumed not to be aircraft, since if they were aircraft their pilots would have contacted the air traffic control agency for that airspace to request a permission to enter. Most air traffic inside controlled airspace is flying according to the Instrument Flight Rules (IFR). Aircraft flying under IFR in controlled airspace are provided with standard separation from other IFR traffic by air traffic controllers. In the majority of cases this separation is provided by means of radar.

In uncontrolled airspace, aircraft may fly without contacting any air traffic control agency. There are two principal types of traffic in uncontrolled airspace in the UK: military aircraft, many of them operating at low altitude, and civil light aircraft. These two categories of traffic are predominantly flying according to the Visual Flight Rules (VFR), under which pilots are responsible

for maintaining their own separation from other aircraft by seeing and avoiding them. Airliners and other commercial aircraft also transit uncontrolled airspace in some areas. Although flying IFR, the pilots of these aircraft are responsible for seeing and avoiding other traffic since they are in uncontrolled airspace. However, since they may be flying in cloud or poor visibility, their ability to see and avoid may be poor or non-existent. Consequently commercial traffic flying in uncontrolled airspace will in almost every case make use of a radar service to provide advice and/or information on other traffic in the area. Over much of the country, this radar service is provided by radar-equipped civil and military airfields under formal contract. This is known as the Lower Airspace Radar Service (LARS). Radar services to aircraft in uncontrolled airspace are also available from other air traffic control units, controller workload permitting.

#### *Proximity to traffic patterns and instrument procedures*

The operational significance of any unwanted returns on radar will depend not only on the type of airspace within which, or underneath which, they are located, but also on their proximity to inbound and outbound traffic routes, holding patterns, and instrument approach procedures. Thus, wind turbines located on the extended centreline of a runway at a radar-equipped airfield are likely to be regarded as a significant problem for controllers. Turbines located under Standard Instrument Departure (SID) and Standard Arrival (STAR) routes may also be considered problematic, although the effects may be limited by the fact that SIDs and STARs are contained within controlled airspace.

#### *Secondary surveillance radar (SSR)*

The discussion so far in this section has related exclusively to primary radar. Some concerns have also been expressed by the Ministry of Defence, the Irish Aviation Authority and other bodies about the impact of wind turbines on SSR. However, experience from other countries (see below) indicates that wind turbine effects on SSR are limited to the physical blanking and diffracting effects of the turbine towers, and that these effects are only a consideration when the turbines are located very close to the SSR. Rotating turbine blades are not considered to have a significant impact on SSR performance due to their low cross-section relative to the size of the beam, and the fact that the returned SSR signal has much higher power than a returned primary radar pulse since it is re-transmitted from the aircraft rather than simply reflected.

In the UK, NATS treats wind turbine proposals within line of sight of SSRs in the same way as it would treat any static physical obstruction. The CAA safeguarding criteria for SSRs require rejection of, or consultation on, any proposed development infringing a 1:200 slope from the antenna, out to a range of 4.6km.<sup>12</sup> SSR is therefore unlikely to feature as a significant barrier to wind power development in the UK.

Unlike countries such as Denmark and the Netherlands, en route traffic over most of the UK is controlled using both primary and secondary radar, usually

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<sup>12</sup> CAP 670, Part B, para 11.4.3.7.3

co-located. This is considered necessary because the UK's more mountainous terrain restricts radar coverage, requiring more radar stations to provide reliable coverage, and because air traffic density is higher in many parts of the UK. The 3nm separation standards applied in most control zones and terminal control areas in the UK are only regarded as being feasible if primary radar is available for verification and as a back-up should SSR fail. The UK also has large areas of uncontrolled airspace where some traffic may not be transponder-equipped. Primary and secondary coverage is essential for provision of radar services in those areas.

In parts of the UK with lower traffic levels, radar services may be provided using SSR only. This applies to predominantly transatlantic traffic at high altitudes off north west Scotland and over south west England, using SSRs at Stornoway and Berrington respectively. The predictable nature of this traffic allows a service to be provided without primary radar. Minimum horizontal separation standards when SSR is used without primary radar are increased to 5nm or 10nm. This is to ensure that separation can be maintained by other means (such as vertically, or by time separation between following flights) should the SSR fail.

## **6. OPERATIONAL EXPERIENCE IN THE UK**

There are numerous cases of wind turbines in the UK which are located within line-of-sight of radars.

### **6.1 Civil airfields**

#### *Leeds-Bradford*

The 23 wind turbines on the Ovenden Moor site in West Yorkshire lie 20km south west of Leeds-Bradford Airport. Ovenden Moor is one of the oldest established wind farms in the UK, having been commissioned in June 1993. The turbines are visible at all times to the airport's Watchman primary surveillance radar as a group of returns. No special processing is applied in the radar to reduce or eliminate the wind turbine returns.

A large proportion of Leeds-Bradford's inbound commercial traffic flies a route from the Pole Hill VOR beacon towards the airport. This route takes aircraft directly over the wind farm. IFR traffic is kept inside controlled airspace as it crosses this area. The base of controlled airspace above Ovenden Moor is at 3000ft amsl. Local light aircraft and military fast jets regularly fly in the uncontrolled airspace below 3000ft in this area. Some of this traffic will appear as primary-only contacts on radar, as do the Ovenden Moor wind turbines.

The radar returns from inbound IFR traffic regularly pass through the clutter created by the Ovenden Moor turbine returns. However the aircraft return always remains distinguishable from the clutter. Controllers at Leeds-Bradford do not limit the service provided to traffic overflying the area of clutter caused by the wind farm.

In addition to aircraft flying over the wind farm within controlled airspace, Leeds-Bradford provides radar services to traffic in uncontrolled airspace up to 42.5nm from the airport. High ground to the west of the airport means that these services are subject to minimum altitude restrictions to the west. Controllers at Leeds-Bradford do not attempt to provide standard 5nm horizontal separation from the clutter created by the Ovenden Moor wind turbines when providing a radar service to traffic in the vicinity of the turbines.

Four wind turbines were commissioned at Chelker Reservoir, 20km NW of Leeds-Bradford Airport, in December 1992. They may also be partly visible to the airport's radar. These turbines are within 3nm of the instrument approach procedures for runway 14 at Leeds-Bradford, and are in an area where IFR traffic may be descending below controlled airspace and may therefore be in airspace also containing unknown traffic. Radar clutter caused by wind turbines in this area might be regarded as requiring measures to separate traffic from the unknown returns. The extent of the visibility of these turbines from the Leeds-Bradford radar, and whether they are treated in the same way as the Ovenden Moor turbines, is not known.

Aircraft in the vicinity of both the Chelker Reservoir and Ovenden Moor turbines include low level military traffic transiting north-south in a narrow corridor over the Pennines. These aircraft are not in radio contact with Leeds-Bradford and generally do not appear on their radar unless they have their transponders switched on.

According to CAA SRG inspectors responsible for regulation of air traffic services provision at Leeds-Bradford, no concerns have been raised about the effects of the wind turbines on Leeds-Bradford's radar, either through personal contact or through formal reporting mechanisms such as the Mandatory Occurrence Reporting (MOR) scheme.

#### *Prestwick Airport*

Prestwick Airport's Marconi EN4000 primary surveillance radar is line of sight to two operational wind farms - Hare Hill, 17.5nm to the south east, and Windy Standard, 19nm away, also to the south east. Neither wind farm was visible on the Prestwick radar until a major upgrade of the equipment was completed in autumn 2000. Since then, both wind farms have been visible to varying degrees.

Hare Hill lies on the extended centreline of Prestwick's main runway, 31. All 20 turbines are visible to the radar, creating an area of primary returns extending up to 1.5nm across and 1.5nm deep. Within this area, individual returns appear intermittently, giving the appearance of a 'twinkling' effect. This could give the appearance of a primary-only target moving across the area between one sweep of the radar and the next.

Six of the turbines on the Windy Standard site are wholly or partially visible to the Prestwick radar. However the return from the turbines always appears as a stationary object, with no obvious signs of movement.

The reasons for the appearance of the Windy Standard turbines as a stationary return while Hare Hill presents a shifting radar image are not known and may be the subject of further investigation. However it is believed that the temporal threshold filtering process of the radar may be responsible for the fluctuating visibility of Hare Hill. This process is performed after the basic MTI function has deleted all static targets. The purpose of temporal threshold processing is to deal with static or slow-moving targets which MTI has failed to eliminate from the screen. These are targets which have some motion, but which remain in the same location – such as a hovering helicopter, or swaying trees in a high wind.

Rotating wind turbines may continue to appear since the moving blades will impart a phase shift to the returned radar pulses in the same way as a genuine moving target. Temporal threshold processing analyses the clutter level in each temporal cell (which consists of a number of individual range-azimuth cells) over successive antenna sweeps. If targets which have some Doppler content, but which do not move outside the boundaries of the cell, appear in a temporal cell the radar processor will raise the clutter threshold by a specified amount, in order to attempt to eliminate the unwanted targets.

The Prestwick radar takes a full 32 sweeps of the antenna to complete adjustment of the clutter threshold levels. If the strength of the wind turbine returns is sufficiently large, the processor will progressively raise the threshold until the clutter is deleted. In the case of wind turbine returns, it is believed that shifts in wind direction or lack of coincidence between blade orientation and radar sweep result in an absence of hits from the turbine blades, causing the temporal threshold filter to reset to zero. It will then recommence adjustment of the threshold as turbine returns appear again.

Prestwick Airport has no controlled airspace in its vicinity below 5500 feet. The area to the south and south-east of the airport is in regular use as a military low flying training area. This is also the sector from which most of Prestwick's inbound commercial traffic arrives. These arriving aircraft are required to descend into uncontrolled airspace for some 20nm before reaching the Prestwick Aerodrome Traffic Zone. This places these aircraft in an air traffic environment where unknown traffic may appear with short notice, the worst case scenario – in terms of the potential consequences – being a military jet pulling out of the low flying system, for example due to deteriorating weather, and initiating a rapid climb to safety altitude. These conflicting aircraft may be invisible to the Prestwick radar due to intervening terrain when they commence their pull-out.

The Prestwick Airport authorities have expressed concern that clutter from a wind farm could hide unknown traffic of this type for a crucial period, preventing controllers from issuing timely warnings to traffic to whom they are providing a service. Air traffic controllers at Prestwick Airport have obtained CAA approval for two procedures to mitigate this risk around the Hare Hill wind farm. The procedure preferred by Prestwick is to vector all traffic around the clutter by 5nm in order to maintain standard separation from any aircraft which might appear from within the area of clutter. The other procedure is to route aircraft over, or closer than 5nm to, the wind farm area, but to formally limit the radar service provided. This will usually consist of advice to the pilot that there may be late warning, or no warning, of conflicting traffic from below due to an area of radar clutter. The official CAA circular on this topic advises that "the pilot is expected to take the warning into account in his general airmanship."<sup>13</sup> This would normally include increased visual lookout for any conflicting traffic if the aircraft is not flying in cloud.

As outlined above, limitation of a radar service is regularly employed by radar units for a variety of reasons and is accepted as an inevitable consequence of the technical limitations of radar. In Prestwick's case, while the problem is highlighted by the location of Hare Hill directly under the main approach path to the airport, there are a number of circumstances which will mitigate the risk in practice:

- the probability of a military jet making its first appearance on radar when directly over the wind farm is extremely small given the number of low

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<sup>13</sup> United Kingdom Aeronautical Information Circular 2/2001 (Yellow 33), 11 January 2001, *Services to Aircraft Outside Controlled Airspace*, para 4.6.2.

- level flights in this area and the frequency with which low level pull-outs occur;
- because of the speed of jet aircraft, traffic is unlikely to be illuminated by the radar for more than one sweep of the antenna while over the wind farm;
  - for a problem to exist as a result of an aircraft appearing on radar for the first time as it crosses the wind farm, the controller would have to be looking at that part of the screen at the time the aircraft was crossing the wind farm;<sup>14</sup>
  - military aircraft are required "whenever possible" to have their SSR transponders switched on when operating in the low flying system.<sup>15</sup> Because of the higher power of the returned signal, SSR returns are usually visible at longer ranges and lower altitudes than primary returns. This will mean that controllers may be alerted to the presence of unknown traffic before the primary return appears;
  - if an unknown aircraft flying across the wind farm area is displaying an SSR return, it will be more visible on the screen and less likely to be lost in the clutter.

The viability of mitigation procedures such as those adopted by Prestwick depends on site-specific circumstances. While procedural measures may be possible for one wind farm, airspace constraints may preclude adoption of similar measures in relation to any additional wind farms. Viability will also depend on the location of the wind farm relative to runway orientation, approach and departure paths, instrument approach procedures, navigation aids and holding patterns.

#### *Aberdeen Airport*

A single wind turbine has been in operation at Bogfechel Farm, Whiterashes, under the final approach track to the main runway at Aberdeen Airport, since the mid-1980s. The turbine is believed to be partially visible to the NATS Plessey Watchman radar on Perwinnes Hill, 7.2km SE of the wind turbine. Perwinnes Hill supplies primary and secondary data to controllers at Aberdeen Airport and to the Scottish Area Control Centre at Prestwick. Primary data from Perwinnes Hill received at Aberdeen Airport has already been processed, with both MTI and plot extraction applied to remove ground clutter and successive plots not meeting specified criteria for the formation of tracks. No returns from the area of the turbine have been noted by controllers at Aberdeen.

However, the visibility of the turbine from the radar head has not been definitively established, and since the turbine is not in continuous operation it may be less apparent to controllers.

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<sup>14</sup> In the report on an airprox incident south east of Prestwick in April 2000, the UK Airprox Board pointed out that the controller had not noticed a conflicting Hawk aircraft on radar for a period of some two minutes before it turned towards a Boeing 737 on approach. UK Airprox Board, *Analysis of Airprox in UK Airspace*, Report No.4, January 2000 to June 2000, pp.127-8.

<sup>15</sup> Royal Air Force Flight Information Publication, *En Route Supplement: British Isles & North Atlantic*, 27 April 2001, 'SSR Procedures – Military Low Flying System', p.300.

### *Newcastle Airport*

A three-turbine wind farm became operational at Kirkheaton, just under 10nm NW of Newcastle Airport, and just outside Newcastle's controlled airspace, in May 2000. The project was submitted to consultation with both the CAA and the MoD with no objections raised.

Newcastle operates a Marconi S511 hybrid primary surveillance radar. The Kirkheaton wind farm appears intermittently on the radar display. With some clutter suppression applied, the turbines appear in a similar way to a permanent echo, with variation in visibility believed to be due to atmospheric conditions. However the return is not regarded as significant since the echo is small and well known, and has not caused any difficulties for ATC staff.

The location of the wind farm only 2nm beyond the Newcastle Control Zone boundary and in the narrow gap between Newcastle's controlled airspace and the RAF Spadeadam electronic warfare training range danger area, is of significant interest to Newcastle ATC, in particular due to their Lower Airspace Radar Service responsibilities. Low level military fast jet traffic is common in this region and a significant amount of light civilian traffic, including training aircraft from Newcastle, use this airspace. There have been several aircraft proximity hazard ('airprox') incidents involving civil and military aircraft in the uncontrolled airspace beyond Newcastle's control zone in recent years, including one in October 1999, shortly before the Kirkheaton wind farm was built, when an RAF Tornado attempting to reach Spadeadam in poor weather flew close to the boundary of controlled airspace and within 1nm of an airliner on approach to Newcastle. The Tornado subsequently crashed only 2km from the wind farm site. In the light of this it could be expected that anything which might have a detrimental effect on radar performance in this area would generate a negative response from controllers.

### *Cardiff Airport*

The Taff Ely wind farm - a 20-turbine development - was established in 1993. It lies 10.8nm NW of Cardiff Airport, within line of sight of the airport's Marconi 511 radar. ATC management advise that the wind farm is visible on their radar display "occasionally, in certain atmospheric conditions", but that it has not caused any operational problems for air traffic at Cardiff.

Taff Ely is in uncontrolled airspace and is not under any of the airport's instrument approach procedures. However, the wind farm is within the airport's Radar Vectoring Area (RVA), and is marked on both the RVA chart, and on the airport's instrument approach charts as a 1184ft unlit multiple obstruction.

When Cardiff traffic is landing on runway 12 (from the west), the wind farm lies under the tracks flown by aircraft inbound to Cardiff from the north via the Brecon navigation aid on airway Alpha 25, and from the west via reporting point Amman on airway Golf One. Scheduled commercial traffic using these routes includes some 15 flights a day from Scotland, Ireland and the north of England.

Cardiff Airport also provides approach radar services for nearby RAF St Athan. St Athan arrivals from the north may also be vectored close to Taff Ely.

CAA SRG staff responsible for inspection and approval of Cardiff Airport's ATC services are aware of the wind farm's existence, but no concerns have been raised about possible effects of the wind turbines on the radar services provided by Cardiff.

#### *Glasgow Airport*

The former National Engineering Laboratory has operated a wind turbine trials site on Myres Hill, 12.2 nm from Glasgow Airport and within the Glasgow CTR, since the 1980s. The turbines are believed to be line of sight to Glasgow's radar. ATC personnel at Glasgow advise that the turbines have not caused any problems. No objections were raised by Glasgow Airport or the CAA to a more recent proposal to develop a commercial wind farm at this location.

#### *Norwich Airport*

The Somerton wind turbine is visible on Norwich Airport's radar. The ATS Manager at Norwich believes that the multiple turbines at Blood Hill are not visible. The return from Somerton, which is 11.5nm from the Norwich radar, is visible intermittently, and appears to move around by 0.25-0.5nm, making it appear similar to a light aircraft return in some circumstances. The movement appears to be because the turbine is situated on the boundary of two range-azimuth cells. Once the controllers had become accustomed to the turbine's appearance on radar, they have had no difficulty in recognising its returns. Traffic is quite dense in this area, but the wind farm is not under Norwich's final approach track or procedures. Radar services are not limited in the vicinity of the turbine returns.

#### *Belfast Airport*

The Elliott's Hill wind farm, consisting of 10 turbines, lies 10nm NNE of Belfast Airport. The turbine tips are 900ft higher than the airfield and the turbines are visible from the airport by eye.

Belfast has a Marconi EN4000 with a Watchman antenna (similar to the equipment at Prestwick). The turbines do not appear on the radar. The airport's ATC engineering manager believed this could be because the turbines are just below the radar antenna beam, which is set at 1.5° in order to reduce the effects of clutter from the ridge of high ground 7nm east of the airport. Most traffic using Belfast is arriving from the east and south so Elliott's Hill is not in a sector of major interest to controllers; nor is it under any of the instrument approaches, so the precise reasons for its non appearance have not been investigated.

## 6.2 Military airfields

### *RAF Marham*

RAF Marham's Watchman radar has a clear view of the full rotor disc of the single E66 turbine on the north side of Swaffham, Norfolk. However the turbine only shows intermittently on the radar, and the returns from the turbine do not present any difficulties to air traffic controllers at Marham. No special processing has been applied to the Marham Watchman radar to reduce the turbine's signature. RAF Marham had intended to object to the construction of the Swaffham turbine when it was proposed, but their objection was submitted too late to be considered in the planning process. However the basis for the objection was not the possible effects on radar, but the fact that an unlit 300ft+ structure in this area could be an obstruction hazard to low flying aircraft.

### *RNAS Culdrose*

A 14-turbine wind farm was established 3.5nm from RNAS Culdrose's Watchman radar in 1993. The following year, the RAF Signals Engineering Establishment carried out a trial to assess the impact of the wind farm on the radar. The report of the trials concluded that the wind farm had a negative impact on the radar's performance, notably in degrading the ability to track aircraft targets over the wind farm area. The report's conclusions have since formed much of the basis for the Ministry of Defence's policy in relation to wind farms visible to radars.<sup>16</sup>

Two features of the Culdrose study are notable:

- the Goonhilly turbines are only 3.5 to 3.8nm from the RNAS Culdrose radar, a much shorter distance than most other wind turbine-radar situations, at least in the UK.
- the RAF SEE trials did not consider whether the radar returns from the wind turbines were operationally significant.

Consultations with air traffic control personnel at RNAS Culdrose have determined that the turbines remain visible on the station's radar. However, suppression of the returns from the wind farm region is applied using RAG (range azimuth gate) mapping techniques. With suppression applied, ATCOs have experienced "some degradation" of radar performance in the region around the wind farm. The extent and nature of the degradation is unknown, but is being monitored by ATC staff at Culdrose as part of an ongoing RAF SEE (now DCSA (DEI)) interest in this case. According to RNAS Culdrose, any degradation of radar performance that does exist is insignificant operationally since the bulk of the traffic operating in the area around the wind farm is VFR and the location is well away from the airfield's instrument procedures. No special measures are applied to route aircraft away from the wind farm, and published procedures for RNAS Culdrose make no reference to radar performance degradation due to the wind turbines, though they are listed as a vertical obstruction.

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<sup>16</sup> *Study into the Effects of Wind Turbines on Radar Performance*, RAFSEE Technical Report No.94010, December 1994.

On the second aspect of radar performance degradation identified in the 1994 RAF SEE report - the possible shadowing of targets behind the wind farm - SATCO Culdrose advised that the evidence is unclear. Targets operating in this area - typically, helicopters operating at low level over the sea in excess of 7 nautical miles from Culdrose - do appear on the Culdrose Watchman. However, since this is an area where aircraft may be operating autonomously, not under Culdrose's control, it has not been possible to assess whether the radar is seeing all targets flying in this region, and if not, whether any loss of targets is due to the wind farm.

#### *RAF St Mawgan*

Two wind farms have been in operation within line of sight of RAF St Mawgan's primary surveillance radar since the early 1990s - Carland Cross, a 15-turbine site 5.3 nm from St Mawgan, and St Breock, an 11-turbine development 8.2nm from the base's radar. In addition a third, 16-turbine development has been approved, following detailed consultations with MoD technical authorities, on Bear's Down, 4nm from St Mawgan's radar. Images of the St Mawgan radar display taken in January 2001 show that the Delabole wind farm, 17nm NNE of St Mawgan, is also visible to the radar.

Since the construction of Carland Cross and St Breock and the approval of Bear's Down, St Mawgan has replaced its AR15 surveillance radar with a Watchman. This has recently been upgraded with colour raster scan displays. SATCO RAF St Mawgan advised that both St Breock and Carland Cross were visible on the AR15 display and now show more clearly on the Watchman. Both sites are treated as permanent echoes, but MTI processing does not remove their returns. The precise effect for aircraft targets crossing the wind farms was not known since the new colour displays had only been installed recently. Further suppression measures were thought to be possible but the SATCO noted that St Mawgan frequently provides radar services to aircraft NE of the base and the cumulative impact of suppression of both St Breock and Bear's Down might degrade this service.

At present, however, the Deputy SATCO at RAF St Mawgan advises that "although the [wind] farms paint quite effectively on radar we do not find that they cause any major problems for our controlling...We count the farms as permanent echoes and do not avoid them as radar contacts. We do, however, limit service when close to them in case 'pop up' traffic appears in that area."

#### *RAF Coltishall*

The Blood Hill wind turbines lie 11.6nm from the radar at RAF Coltishall; the single Somerton turbine is 11.2nm from Coltishall. The Deputy SATCO at RAF Coltishall, which provides area radar services to civil and military traffic in the area, confirmed that returns from the turbines are visible on their Watchman radar, but do not affect ATC operations. The return is very small, remains static, and is present for 95 to 99% of the time. This may indicate that only the single turbine at Somerton is visible. The position of the return was plotted as a permanent echo when the turbine was built.

#### *Other UK military radars*

One further military airfield in the UK with experience of accommodating wind turbine effects on radar was consulted but the base SATCO was unwilling to co-operate with the study.

RAF Neatishead, an air defence radar station east of Norwich, was also approached for information on the impact of the Blood Hill and Somerton wind farms on their operations, but declined to participate on grounds of national security.

### **6.3 En route radars**

#### *Trimingham*

NATS operates an en route radar facility at Trimingham, near Cromer on the Norfolk coast, providing a radar service (Anglia Radar) primarily for helicopters operating to and from offshore installations in the southern North Sea. The radar is 17nm from the Blood Hill and Somerton wind farms. Anglia Radar's controllers are based at Aberdeen Airport and use data derived from several radar heads including Claxby, near Market Rasen in Lincolnshire, and Trimingham. Raw returns from the primary radar are processed to provide correlation with SSR data and to reduce the size of the returns.

The Blood Hill/Somerton wind turbines paint intermittently on the Trimingham radar in the form of small points. The return occasionally shifts laterally, possibly indicating alternate illumination of different turbines. The maximum lateral distance over which the turbine returns may be visible is less than one nautical mile. The turbine returns are well known and recognised by controllers and are not regarded as presenting any difficulties to the controllers' task. Most traffic in the immediate area is helicopters following recognised and regular tracks, and all traffic to which a service is being provided will be transponding. Low level military fast jet traffic is also common in the area but the vast majority of this traffic is also transponding.

The turbine returns do not constitute a significant enough area of clutter to warrant limiting the radar service to transponding traffic. However controllers might limit the service to traffic for which only primary radar data was available (i.e. aircraft which do not carry an SSR transponder or do not have it switched on).

#### *Lowther Hill*

The NATS en route radar on Lowther Hill is line of sight to two wind farms - Windy Standard (15.5 nm) and Hagshaw Hill (12 nm). NATS engineering and operational support personnel at the Scottish Area Control Centre (ScACC) advise that no concerns have been raised about returns from these wind farms. Recent upgrades of the MTI software on the Lowther Hill radar have improved its ability to filter out road traffic which may also assist in suppressing any wind turbine returns. However no specific processing has

been applied to this or any other NATS en route radars to mitigate any effects from wind turbines.

The Lowther Hill radar antenna is located approximately 2400ft above sea level. Since it is an en route radar, it is optimised for coverage of higher altitudes. NATS engineering staff report that the Hagshaw Hill turbines (blade tip heights up to 1720ft amsl) may be below the antenna beam coverage from Lowther Hill, in which case they would not be illuminated by the radar and would not appear on the radar screens. During the planning consultations for the Windy Standard wind farm ScACC is understood to have considered applying a limitation to the Lowther Hill radar antenna beam elevation in order to prevent the radar illuminating the turbines, if interference was found to be a problem. However no such limitation has been applied. The Windy Standard turbines extend to a maximum height of 2406ft amsl.

Secondary surveillance radar data from Lowther Hill is also supplied to a number of third parties including Prestwick and Edinburgh Airports. Reflection of SSR signals by a wind turbine more than 10nm away is considered by NATS radar engineering staff to be very unlikely and no problems have been reported. NATS practice is to assess potential wind turbine effects on SSR purely in terms of the static obstruction presented by the turbines, in the same way as electricity pylons or radio masts would be assessed. Rotating turbine blades are not considered to have a detrimental effect on SSR.

## 7. OPERATIONAL EXPERIENCE OUTSIDE THE UK

### 7.1 Netherlands

#### *Amsterdam (Schiphol) Airport*

Fourteen turbines with a maximum blade height of 89m were constructed in the Amsterdam Western Harbour area, 10km north of Schiphol Airport, in 2000-2001. The turbines are all located within controlled airspace. They are positioned under the final approach path to runway 19L at Schiphol. This runway is only used for landings in daylight visual conditions (no night or instrument approaches permitted), but a surveillance radar approach is available which involves radar vectoring to a point approximately two nautical miles from touchdown. In addition, the radar at Schiphol, which is located on top of the elevated control tower at the airport, is estimated to be line of sight to:

- four 53m turbines in controlled airspace at Haarlem, 15km NW
- five 45m turbines outside controlled airspace at Velsen, 20km NW
- ten 100m turbines outside controlled airspace at Flevoland, 25km ENE.

According to the Dutch air traffic control authority, LVNL, there have been no indications to date that any of the above wind turbines appear on their radar. LVNL is aware of the theoretical possibilities of diffraction, screening and false returns due to rotating turbine blades, but none of these effects have been experienced.

In the case of the Western Harbour turbines, the Dutch planning consultation process, which requires developers to consult the airport if proposing construction in the vicinity, failed to alert the authority to the proposal. However no effects have been experienced.

Schiphol's primary radar is an Alenia ATCR-33K, with a G-33 antenna. This is a relatively modern radar although it is the klystron-based (not solid state) version of the ATCR-33, which has less capability at eliminating clutter. The ATCR-33 employs MTD processing and incorporates several clutter maps. These processes are effective at eliminating moving returns from road traffic around Schiphol as well as the wind turbines.

#### *Leerdam*

One of the most important en route radar facilities in the Netherlands is located at Leerdam, south of Utrecht. In the late 1990s, when the Luchtverkeersleiding (LVNL - Dutch air traffic control authority) was planning replacement of the SSR equipment at Leerdam with new Mode S radars, a proposal was made for a wind farm close to the site. The closest turbine would have been 1.1 km from the radar and the wind farm would have extended over azimuth angles of up to 55° and elevation angles up to 2.3° as viewed from the radar. LVNL asked the two leading manufacturers of SSR, Raytheon Systems and Airsys ATM, to assess the likely impact of the proposed turbines on the Leerdam SSR.

Raytheon Systems engineers predicted that diffraction of the SSR signal by the turbine towers could cause azimuth inaccuracies on aircraft targets in the area up to 3° either side of each wind turbine tower, and some obscuration of targets behind the wind turbines. Raytheon recommended that the turbines be placed further away from the radar and that they should be realigned to present less of an azimuth extent to the radar, for example by aligning turbines one behind the other along a radial from the radar.

The assessment only considered the effects on SSR of the static tower structure of the turbines. The rotating turbine blades were not considered to have any obscuration effects since any scattering or reflection would be fleeting and would only affect a small proportion of the radar beam's energy.

#### *Military air bases*

Primary surveillance radars at the Dutch Air Force bases at Leeuwarden, Twenthe and Soesterberg are affected to varying degrees by wind turbines within line of sight. The primary radar equipment at these airfields is the Raytheon ASR-910B which is a 20-year-old design. Woensdrecht air base, in the south of the country, which currently has no radar, may be affected in future if proposed installation of a Raytheon ASR-10SS primary radar goes ahead. Woensdrecht has two multiple turbine wind farms within 12km and four within 25km.

At Leeuwarden, in Friesland, there are four multiple-turbine wind farms within 15km of the base. Concerns about the impact of these turbines on radar coverage of low level traffic beyond the turbines led the Dutch Air Force to commission research on the problem from the FEL-TNO research agency in The Hague.

FEL-TNO's research focused on the 'shadow' effect on radar coverage behind a wind turbine, using a computer program which predicts the forward scattering by turbines. However the research did not investigate the impact of the rotating turbine blades on radar performance since the radars under consideration were non-coherent and regarded as not susceptible to signal back-scattering by rotating blades.

The practical effects on the radar at Leeuwarden do not include difficulties in tracking aircraft crossing overhead the areas of the wind turbines.

A contract to upgrade the existing Raytheon ASR-910B aerodrome surveillance radars at military air bases in the Netherlands is currently under consideration. Replacement is not, however, driven by the desire to overcome problems created by wind turbines.

## **7.2 Denmark**

Denmark has the highest concentration of wind turbines of any country in the world. Data obtained from Vane Consulting in Denmark indicates that there are 1811 existing wind turbines within 30km of air traffic control radars in

Denmark, and a further 570 turbines within 30km of five GCI (air defence) radar stations. These figures include substantial numbers of single turbines which mostly have tower heights less than 30m. However due to the predominantly flat terrain in Denmark, even these smaller turbines are likely to be visible to radars.

Full consultation with all radar-equipped airports in Denmark was beyond the scope of this study. However, consultations with the regulatory authority, Statens Luftfartsvesen (SLV), the air traffic control provider, Flyvesikringstjenesten, and Danish wind industry companies and consultants, produced a unanimous response that wind turbines presented no difficulties to air traffic control radar operations.

### *Kastrup*

Copenhagen International Airport at Kastrup, south east of the city, has 71 wind turbines within 30km. These include:

- 15 turbines at Avedøre, between 10.4 and 13.1 km west of the airport
- the 20 offshore wind turbines of the Middelgrunden project, 100m in height, between 6.4 and 10.0 km NNE of the airport
- seven turbines at Lynetten, on the edge of Copenhagen Harbour, 9km north of the airport
- eight turbines at Dragør, on the southern airfield boundary, only 4km from the airport's primary radar, less than 2km from its secondary surveillance radar, and adjacent to the airport's principal radio navigation aid, the Kastrup VOR.

The Middelgrunden turbines, completed in 2000, lie directly under the missed approach path for runway 04 and under the instrument approach procedures for runway 22. Avedøre lies under the instrument procedure for runway 12.

Kastrup's primary radar is a Texas Instruments (Westinghouse) ASR-8, with an Airsys ATM TPR-1000 track processor. The TPR-1000 performs plot extraction, track correlation and primary-secondary plot correlation functions. According to the Flyvesikringstjenesten engineering manager for the Kastrup radar, while the raw output from the ASR-8 may be able to detect wind turbines, the TPR-1000 will process them out. Wind turbines consequently have "no effect whatsoever" on the radar display at Kastrup. This is also true for the Thomson-CSF RSM 970 SSR which is located at the southern end of the airport, less than 2km from the Dragør wind farm.

### *Aalborg*

The airport at Aalborg is a joint civil/military facility, with regular scheduled services and fighter jet operations. There are currently 425 wind turbines at distances ranging from 3km to 30km from the airport. These include several large groups of turbines immediately south of the approach path to the main runway, 26, at a range of 6.5 to 7 nm, several turbines under the instrument approach procedures for runway 08, and numerous turbines under the VFR approach routes to the airfield from the north.

Other radar-equipped airports in Denmark with wind turbines within 30km are Aarhus (Tirstrup), Billund, Karup, Skrydstrup/Vojens, Roskilde and Vaerloese.

UK CAA SRG officials have pointed out that policies on air traffic management in Denmark are different from those in the UK and that this may account for Denmark's greater willingness to accept wind turbines. The key differences are, first, that Denmark does not use primary radar for en route air traffic control, relying solely on SSR for this task. SSR is less vulnerable to wind turbine effects. Second, SRG would not permit plot extraction over areas of clutter in the way that Kastrup does.

Further evidence on the comparison of Danish and UK regulatory policy in this area is required, notably on the experience of airports other than Kastrup, the acceptability in practice of plot extraction in en route radars and in controlled airspace in the UK, and Danish radar coverage of traffic outside controlled airspace.

### **7.3 USA**

#### *Stockton, California*

Raytheon Canada have installed an all solid state S-band ASR-10 radar for the Federal Aviation Administration (FAA) at a site near Stockton, east of San Francisco. The radar is within line of sight of a number of wind turbines. According to Raytheon Systems and the FAA, although the radar employs digital processing, it has only three Doppler filters and has not been entirely successful in filtering out wind turbine returns. Raytheon engineers also found that the wind turbines had a slight skewing effect on the radar's antenna beam, causing some azimuth errors.

#### *Palm Springs, California*

A new Northrop-Grumman ASR-9 primary surveillance radar became operational at Palm Springs in January 2001. This replaced an ASR-8 which had suffered considerable problems due to clutter from the many wind turbines in the Palm Springs area. Wind turbine clutter had led to limitation of radar service to aircraft in the areas around the wind turbines.

The ASR-9 was the first radar to use MTD technology, providing a vast increase in performance over MTI radars. The ASR-9 at Palm Springs has modifications applied which originated from FAA engineering research to deal with radar clutter from migratory birds in the San Francisco area. The modifications in the Palm Springs radar include dynamic clutter mapping and six Doppler filters, providing much enhanced sensitivity to moving clutter at different velocities. Air traffic controllers at Palm Springs are now able to vector traffic across the wind turbines without any detrimental effect on radar performance since the turbines no longer appear on the radar screen. No limitation of radar service is required.

*Edwards Air Force Base*

The Tehachapi Pass in California, on the north west edge of the Mojave Desert, has the highest concentration of wind turbines in the USA. Edwards Air Force Base, home of the Air Force Flight Test Center (AFFTC), lies 20nm south east of Tehachapi Pass. AFFTC's extensive facilities include multiple test areas and ranges to support the USAF's aircraft, equipment and weapons test and evaluation activities. Among these facilities are three low level flight routes across the Tehachapi Pass for test aircraft. A further three low level routes run across the pass, used by Air National Guard C-130s, US Navy F-18s and US Marine Corps aircraft.

## 8. MITIGATION TECHNIQUES

### 8.1 Radar processing

Primary radars will detect any targets which meet the thresholds, or criteria, set in the radar's processing. Radar performance is determined by the balance between the probability of detecting wanted targets (probability of detection,  $P_d$ ) and the probability of detecting unwanted or false targets. The ratio between these two probabilities is known as the false alarm rate. Measures to increase the probability of detecting wanted targets may also increase the probability of false or unwanted detections. A number of measures can be used to improve a radar's ability to discriminate between wanted and unwanted targets.

#### *Amplitude thresholds*

If the unwanted targets (such as rain or birds) are expected to have a lower radar cross-section than the desired targets, the amplitude of the unwanted returns can be expected to be lower than that of the genuine targets. A voltage threshold can be set in the radar causing returns below a given amplitude to be ignored. However, wind turbines can have radar cross-sections larger than aircraft targets so this method has very limited utility.

#### *Range-azimuth gating (RAG)*

This process identifies particular range-azimuth cells, or groups of cells, within which returns are suppressed. RAG usually involves suppression of all returns from the identified cells, creating a hole in the radar cover.

#### *Constant false alarm rate*

A development of the amplitude threshold method is to apply thresholds which will maintain a constant false alarm rate (CFAR). This process, also known as temporal threshold processing, is designed to maintain radar performance in areas where there is clutter. A threshold is set for a group of range-azimuth cells. If the largest return from that area in one antenna sweep is of greater amplitude than the largest return from the previous antenna sweep, the threshold is increased to try to eliminate the clutter. After several antenna revolutions the threshold will rise sufficiently to eliminate the clutter.

This process is quite effective in removing shifting clutter returns from the radar screen. However, if a desired target within the area has a weaker return than the clutter, or if it stays within the area for several antenna sweeps (as for example a hovering or slow-moving helicopter might), the clutter threshold will eliminate that genuine target as well as the clutter.

#### *Doppler discrimination*

Radars can discriminate between wanted moving targets and unwanted static or slow-moving targets by processing out those that do not exceed a given radial velocity. This is done by detecting differences in the phase - Doppler shift - of consecutive return pulses received by the radar. Leaving aside aircraft flying tangentially to the radar, which will have a low radial velocity, most clutter will have lower Doppler values than aircraft returns. However,

wind turbines are problematic since blade tip speeds may be as much as 120 knots, similar to the speed of a light aircraft or helicopter.

There are two established methods of Doppler processing in radars to suppress slow-moving or static clutter while maintaining detection of aircraft.

#### *Moving target indication (MTI)*

MTI processes several consecutive returned pulses. The output of this process identifies any object with zero Doppler, i.e. which is static, and can then eliminate that object from the radar display. Basic MTI can only eliminate static objects. Adaptive MTI (AMTI) not only filters out the fixed clutter, but also estimates the predominant Doppler value of the remaining, moving clutter in each range-azimuth cell, and filters it out. AMTI can therefore cancel out moving as well as fixed clutter.

#### *Moving target detection (MTD)*

MTD is also based on analysing the characteristics of a series of consecutive returned pulses. MTD has the ability to generate a number of filters corresponding to different velocity ranges, thus giving the radar greater ability to discriminate between returns with different velocities. However both MTI and MTD are dependent on there being some measurable difference in the Doppler values of genuine targets and those of any clutter or unwanted targets. Greater discrimination between different Doppler values requires a higher pulse repetition frequency (PRF). Because correct measurement of range depends on a returned pulse being received before the next pulse is transmitted, the higher the PRF, the lower will be the maximum unambiguous range of the radar. Thus MTD is usually less suitable for en route radars, which have a lower PRF in order to achieve longer range.

MTD also requires greater processing power. This is a limiting factor for many older technology radars, and restricts the most sophisticated Doppler filtering techniques to the latest solid-state radars.

#### *Clutter maps*

Point clutter such as buildings, towers, chimneys and radio masts, and much ground clutter, is predictable and unchanging. Rather than requiring the radar to analyse and detect this clutter and process it on every antenna sweep, using up processor power, the clutter characteristics can be stored in a memory circuit, which is then accessed on each sweep to remove that clutter from the signal. This is known as a clutter map.

Some radars have numerical limits on the number of range-azimuth cells which can be used for clutter mapping or RAG techniques. The total number of cells available may not be sufficient to accommodate processing of all clutter sources visible to the radar, especially where extensive wind farms are involved.

#### *Automatic tracking*

Further processing can include automatic detection of aircraft tracks. This is based on analysis of successive returns from a target to determine the

direction and speed of its movement. Automatic tracking radars will display only targets meeting the specified track criteria so, for example, returns which do not match the speed characteristics of an aircraft will not be displayed. This process is also known as plot extraction. The screen display has no 'raw' radar returns but shows confirmed tracks as a line indicating the direction of the movement, the length of the line indicating the speed of the aircraft.

Plot extraction can be further developed so that the track of an aircraft can be projected through an area of poor coverage by 'coasting'. This involves the track processor predicting where the next plot from the aircraft will be, given its track history in terms of speed and direction. Coasting can therefore allow tracking to continue over areas where the radar may not actually be illuminating the aircraft. Tracking processors can also suppress track initiation in selected areas. This will reject any track which first appears in a selected area (such as a range-azimuth cell containing a wind turbine) but will retain pre-existing tracks which have entered that cell from elsewhere.

Acceptability of this type of processing will depend on the probability of an aircraft first appearing on radar in that cell and the probability that it will generate a track on moving into adjacent cells. Probabilities will be dependent on the physical dimensions of the range-azimuth cell. The smaller the cell, the smaller the impact on radar coverage area, and also the less time aircraft will spend in each suppressed cell. As a guide, a typical FAA-specification airport surveillance radar has range-azimuth cells measuring  $0.75^\circ$  in azimuth (242m wide at 10nm range from the radar) by  $1/16$ nm (115m) in range.

Acceptability of track initiation suppression will also depend on the traffic mix. If slow moving, non-transponding traffic such as helicopters or light aircraft are likely to fly in the area, regulators may regard track initiation suppression as unacceptable.

#### *Antenna elevation*

Evidence from Belfast suggests that wind turbine clutter may be avoided by raising the antenna beam elevation angle. Air traffic service providers may be less willing to contemplate such a measure for a man-made development than they would for unavoidable causes of clutter, such as terrain, but experience with proposed measures to mitigate the effects of the Windy Standard wind farm on the Lowther Hill radar suggests that this may be a feasible technique. It is likely to be more applicable in the case of en route radars than for aerodrome surveillance radars since coverage at lower levels is more important for the latter.

#### *Mitigation policy and practice*

There appear to be inconsistencies in the application of radar safeguarding policy with respect to wind turbines in the UK. CAA SRG officials have stated that the processing out of wind turbine returns on radar, whether by eliminating all returns from particular regions (through such techniques as range-azimuth gating) or by use of multiple Doppler filters to screen out

targets meeting specified velocity criteria, is unacceptable since there can be no guarantee that these processes will not also eliminate genuine targets such as slow-moving helicopters or light aircraft.

However, in practice, a variety of radar processing techniques are already applied in radars in the UK to eliminate weather clutter and road traffic in particular. These techniques are likely to involve some degradation of the radar's capability to detect targets moving at similar velocities - again, typically, slow-moving helicopters and light aircraft. In some controlled air traffic environments, this degradation of primary radar performance will be of little or no concern because helicopters will be using transponders and non-transponder-equipped light aircraft are not permitted in the airspace. However in uncontrolled airspace, or categories of controlled airspace where non-transponding VFR traffic is permitted, these processing techniques will already be reducing radar performance against some traffic.

Processing techniques such as plot extraction are also widely used in NATS radars. At Aberdeen Airport, for example, approach radar services are provided using data from the nearby dual-function (en route/aerodrome) Perwinnes Hill radar head. Plot extraction is performed at the radar site and the processed data fed to Aberdeen Airport by modem. This processing eliminates any targets which do not move by a defined amount within a specified time period. This would include, for example, a hovering or slow-moving helicopter. The acceptability of this type of processing at Aberdeen is notable given the high volume of helicopter traffic there.

Further, NATS has given approval for suppression of wind turbine returns in at least one case involving a large wind farm proposal in an important area for commercial air traffic near a civil airport.

Some mismatch between responses to wind farm development proposals and existing operational experience is also evident in the Ministry of Defence. The operational significance of particular wind turbine impacts on radars at RAF airfields in the UK is assessed by staff at HQ RAF Strike Command Operational Support (ATC). Each case is considered on its merits, taking account of proximity to runways, flight paths and instrument patterns. Cumulative impact of several wind farms within line of sight of a radar are a growing concern. However, although the RAF safeguarding policy document, AP100G-03, sets out limits for the total angular extent of any obstructions for secondary surveillance radars,<sup>17</sup> no such criteria are applied in the case of primary radar. Assessment of operational significance is based on professional judgement taking into account the specific circumstances of each case. Experience at RAF St Mawgan and other military airfields indicates that professional judgement of air traffic control safety specialists may permit multiple wind turbines in several sectors.

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<sup>17</sup> AP100G-03, *Site Restrictions for Ground Radio Installations*, October 1991, Chapter 3-17.

*Technical feasibility*

A large proportion of the ATC radar infrastructure at UK civil airports comprises Marconi 511 and Plessey Watchman primary radars. Both equipments are now supported by Alenia Marconi Systems, and impending reorganisation is likely to mean that the formerly physically separate engineering support teams for the two radars will be merged in one location. This should simplify the investigation of both hardware and software solutions which might be applied as an upgrade to existing radars.

## **8.2 Procedural mitigation**

While it is clear that many air traffic controllers are happy to continue providing a radar service over and in the vicinity of clutter from wind turbines without limiting the service, procedural measures can be applied. The two principal procedures are those currently in use at Prestwick Airport - vectoring traffic around the clutter, with the aim of maintaining 5nm separation from the clutter, or limiting the radar service if traffic is vectored over or within 5nm of the clutter. These procedures are applicable to wind turbines located in uncontrolled airspace.

For turbines located in or under controlled airspace, mitigation should not be necessary since unidentified returns can be disregarded. Prestwick Airport has suggested that wind farm clutter within controlled airspace may prevent controllers maintaining standard 3nm separation between aircraft, leading to controllers having to vector traffic around any such clutter, but support for this view has not been found from operational experience elsewhere in the UK.

## **9. APPROACHES TO CONSULTATION AND MITIGATION**

The impending devolution of safeguarding decision-making from the CAA to individual airfields will compound the lack of a clear national basis for decisions on the likely impacts of proposed wind turbines on radar.

The Senior ATCO at Prestwick Airport has suggested that airfields should produce their own safeguarding maps which would indicate the most important areas for clear radar performance as a guide to wind turbine developers. While this approach has much merit, it would need to be underpinned by agreed national standards on how to draw up such maps. Without this, wind turbine development would be at the mercy of varying policies across the country.

In the absence of a sufficiently sophisticated engineering model which can predict the impact of a specific turbine on a specific radar, national policy must be based on current practical experience. The alternative is to base policy on the theoretical possibility of negative effects, as seems to be the case centrally in the MoD, though not at operational level in the armed forces. A policy of objecting to any wind turbine development which might create a radar return would result in continued inability to meet renewable energy targets since large areas of the country would effectively be sterilised for wind energy development.

There is scope for bringing together controllers and engineers with practical experience of the radar-wind turbine issue, and regulators and policy-makers, to explore the ways in which air traffic controllers currently cope with visible wind turbines, and to identify transferable lessons in those cases where wind turbines are not regarded as creating serious problems.

## 10. CONCLUSIONS AND RECOMMENDATIONS

There are clear examples in the UK of co-existence of wind turbines and air traffic control radars. These examples exist at a range of civil and military airfields and en route radar stations. They include several cases where the wind turbines have been in operation for several years without any requirement for intervention by the regulatory/approval authority. The wind power industry should draw these examples to the attention of the key decision-makers in the air traffic control and airfield regulatory/approval authorities and establish a detailed dialogue with those authorities to identify the key determinants of acceptable radar/wind farm co-existence and the operational limits of that co-existence. This may be done under the auspices of the existing Working Group or separately.

Case studies from Denmark, the Netherlands and the USA indicate that technical solutions have been applied which enable radars to process out wind turbine returns while retaining genuine aircraft tracks. While these technologies are particularly available in the most modern solid-state radar designs, there appears to be some scope for retrofitting of advanced processing software to older radars, such as those which make up the bulk of the UK air traffic control infrastructure. The wind industry should consider supporting a feasibility study by the one radar manufacturer now responsible for these older radars, to assess the scope for radar upgrading to process out wind turbine returns.

The CAA has indicated that radar track processing of the type employed in Dutch and Danish ATC radars is not acceptable in the UK. The wind industry should engage the CAA in a dialogue about the reasons for the UK's different policy on this issue, with a view to changing it. The backing of radar manufacturers may be useful in supporting this move.

The CAA has also stated that it does not favour the range-azimuth gating (RAG) approach to eliminating wind turbine returns, which also eliminates aircraft returns from those portions of the radar's cover. However NATS, the main ATC radar operator in the UK, appears to take a different view, even in relation to very large wind farms near busy civil airports. The contradiction between these positions needs to be discussed with the CAA and NATS and a consistent policy developed in consultation with the wind industry.

**AIR TRAFFIC BRIEF**

1. Identify how wind turbines register on a primary radar screen. Explain how a registration from a wind turbine differs from other registers and whether there are similar objects that appear e.g. clouds, rain.
2. With respect to 1 above, what procedures are adopted by air traffic controllers to deal with such situations e.g. offer "reduced radar service", avoidance. What are the implications of the above with respect to CAA procedures and the ability of the airfield to operate within CAA guidelines.
3. What part of a turbine registers on the radar and what is the nature of the signal. Why do turbines appear to move between cells? Could software be developed to deal with this? [it is appreciated that this report may simply recommend an approach to understand this issue more clearly and to ask initial questions of suitable parties on whether there is potential to eliminate responses and whether this is a preferred approach to adopt.
4. Identify the proximity of wind turbines (inc. number/type/variable or fixed rotor) to airfields ~ both military and civilian ~ (including the orientation of the turbines to runways, radar type, etc) in the UK. Determine azimuth extent of site on radar for site and on radar as a whole if more than one site. How have airfield dealt with the presence of wind turbines? Is it an issue and have there been any "incidents". How have these been resolved. Approaches should be verbal initially followed by a written questionnaire.
5. Collect a database of the wider European and American situation and how air traffic services are managed. Have any safety instances relating to turbines been identified? (Note that this is not as important as UK experience as different aviation rules may apply e.g. US).
6. Assuming that wind turbines will appear on the radar screen, what forms of options for mitigation can be taken by a wind farm e.g. alignment of turbines, paints to reduce the radar register, and what mitigation can be taken by the airfield in terms of operation to minimise the effect e.g. extractor radar, redirecting flights, realigning radar, offering "reduced radar information".
7. With respect to 6, determine how any proposed measures must be incorporated as approval procedure measures with the CAA (or other).
8. Advise on a preferred approach procedure for individual sites when assessing air traffic issues and how to approach individual concerns.

**APPENDIX B  
CONSULTEES**

Alenia Marconi Systems Ltd, Chelmsford	
Belfast Airport	ATS Manager
	ATC Engineering Manager
CAA Safety Regulation Group, Air Traffic Service Standards Department	
Cardiff Airport	ATC Engineering Manager
DCSA (DEI), RAF Henlow	
Federal Aviation Administration, Airway Facilities, Western Pacific Region	
Federal Aviation Administration, Palm Springs Air Traffic Control Tower	Air Traffic Manager
FEL-TNO, The Hague	
Försvarets materielverk (FMV) (Swedish Defence Materiel Administration)	Project Leader, Wind Power Project
Glasgow Prestwick International Airport	SATCO
	ATC Engineering Manager
HQ RAF Strike Command Operations Support (ATC)	
Koninklijke Luchtmacht (Royal Netherlands Air Force), The Hague	
Leeds-Bradford International Airport	ATS Manager
Luchtverkeersleiding Nederland (LVNL - Dutch air traffic control authority)	Gen Mgr ATM Development & Support
National Air Traffic Services, Aberdeen	Engineering Manager
	Watch Manager
	Deputy Watch Manager
National Air Traffic Services, Glasgow Airport	
	Watch Manager
National Air Traffic Services, Navigation Services, Spectrum House, Gatwick:	
	Systems Engineer
National Air Traffic Services, Scottish Area Control Centre, Engineering Manager	
Newcastle Airport	ATC Supervisor
Northrop-Grumman, Maryland	
Norwich Airport	ATS Manager
RAF Coltishall	DSATCO
RAF Marham	SATCO
RAF St Mawgan	SATCO, DSATCO
Raytheon Systems Ltd, Harlow	
RNAS Culdrose	SATCO
Vane Consult, Denmark	Director

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