DEPARTMENT FOR BUSINESS
ENTERPRISE & REGULATORY REFORM

# RADAR IN-FILL FOR GREATER WASH AREA

## Feasibility Study – Final Report

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# Radar In-fill for Greater Wash Area Feasibility Study - Final Report

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# Executive Summary

Future Round 2 offshore wind farm developments in the Greater Wash area of the United Kingdom have the potential to cause an unacceptable level of interference to primary air surveillance radars operated by the Ministry of Defence (MOD) at Trimingham and Staxton Wold. Such a loss of radar capability is anticipated to result in planning objections and a delay to the consents required by developers for the construction of Round 2 developments and potential future offshore sites.

This study was commissioned to examine the feasibility of deploying a new radar in the Greater Wash area to provide extra observations around and above offshore wind farms. The new radar would "in-fill" regions of air space where surveillance coverage is predicted to be lost due to interference caused by offshore wind turbines.

The terms of reference were to:

- Clarify MOD requirements concerning air surveillance radar performance in the Greater Wash area;
- Examine how an "in-fill" radar might be used to address the problem, and identify technical uncertainties relating to the effectiveness of such a solution;
- Examine and recommend candidate sites for deployment of an in-fill radar;
- Specify and identify a candidate radar or radars that meet the assumed in-fill requirement, for further assessment and possible procurement;
- Determine how an in-fill radar can be integrated with the existing MOD air surveillance network and define an implementation plan.

Other potential technical measures to help to mitigate the interference problem are the subject of separate studies being funded by other bodies, such as the UK Department of Business, Enterprise and Regulatory Reform (formerly the Department of Trade and Industry). For the purposes of this study, only interference mitigation associated with an in-fill radar was considered, with no assumptions made about the outputs of other related research.

Following inputs on radar user requirements and receipt of background information from the MOD, a set of technical features for a candidate in-fill radar were drawn up by QinetiQ, and a number of radar manufacturers were then approached with a formal request for information. Positive responses were received from five radar manufacturers, who supplied information to QinetiQ on candidate in-fill radar solutions. Due to commercial sensitivities and export control constraints, radar technical information was provided only to QinetiQ under commercial non-disclosure agreements. These limit the extent to which individual in-fill radar solutions can be described in this report. Such material is confined to a report Annex that is not publicly releasable.

The proposed solutions differ in terms of technology employed, the level of detail provided, and product maturity; some companies also provided more than one possible solution. Where possible the results of radar trials involving real equipment observing real aircraft above wind farms were sought and factored into the report's conclusions and recommendations.

# Glossary

| | |
|---|---|
| In-fill | Refers to the removal or mitigation of lost air surveillance capability caused to an existing radar by a new wind farm development. It is not required that additional surveillance capability is provided by the mitigation. |
| TRL | Technology Readiness Level (TRL) refers to the level of technical maturity of a (military) technology on a scale of 1 (low) to 9 (high). |
| TRL 8 | The technology has been proven to work in its final form and under expected conditions. |
| TRL 9 | The technology is in final form and applied under mission conditions, such as are encountered in either operational test and evaluation or in actual operational mission conditions. |

# Acronyms and Abbreviations

| | |
|---|---|
| AOSIPT | Airfield Operations Support Integrated Project Team (MOD) |
| BERR | Department for Business, Enterprise and Regulatory Reform |
| DTI | (Former) Department of Trade and Industry, now part of BERR |
| MOD | Ministry of Defence |
| RAF | Royal Air Force |
| RPM | Revolutions per minute |
| RRH | Remote Radar Head |
| TRL | Technology Readiness Level |
| WP | Work Package |

# 1 Introduction

Future offshore wind farm developments in the Greater Wash area of the United Kingdom have the potential to cause unacceptable interference to primary air surveillance radars at Remote Radar Head (RRH) Neatishead (physically located at Trimingham) and RRH Staxton Wold operated by the Ministry of Defence (MOD). This loss of capability may result in planning objections and a delay to the consents required by wind farm developers for the construction of Round 2 developments and potential future offshore sites.

Existing MOD Type 93 air surveillance radars at Staxton Wold and Trimingham are to be replaced in the near future. It is reported that MOD is planning to replace the radar at RRH Staxton Wold with a RAF Type 101 radar, and the radar at Trimingham with a new Type 102 radar. However, there is currently technical uncertainty as to the degree to which these new features will enable acceptable levels of operation in the presence of wind turbines. There is consequently a need to define, as a risk-reduction measure, further interim solutions that would permit MOD to consent to wind farm development within Round 2 timescales.

This study looks at the feasibility of one specific potential solution: that of deploying a new, shore-based radar in the Greater Wash area to provide extra observations around and above off-shore wind farms. The new radar would "in-fill" regions of air space where surveillance coverage is predicted to be lost by the existing MOD radars, in the presence of Round 2 wind farm developments.

Other potential measures, including stealth technology, either have been, or are being addressed in other studies being sponsored by the Department for Business, Enterprise and Regulatory Reform (BERR) or MOD.

This report describes a feasibility study, contracted by COWRIE with AEA Energy and Environment and QinetiQ, to examine the benefits and practicalities of deploying an "in-fill" radar in the Greater Wash area. The study aims to:

- Clarify MOD requirements concerning air surveillance radar performance in the Greater Wash area;
- Assess the likely impact of wind farms on existing primary radars in the absence of mitigation;
- Examine how an additional "in-fill" radar might be used to address the problem, and identify technical uncertainties relating to the effectiveness of such a solution;
- Examine and recommend candidate shore-based sites for deployment of an in-fill radar;
- Specify and select a candidate radar or radars that meet the assumed in-fill requirement, for further assessment and possible procurement by MOD;
- Determine how an in-fill radar can be integrated with the existing MOD air surveillance network; and
- Defining implementation and operations programmes that address through-life radar costs and procurement time-scales.

The study deliverable is a final report (this document) that summarises conclusions and states recommendations.

# 2 In-fill radar study overview

## 2.1 Study work packages

An overview of the study work packages (WPs) is shown in Figure 1.

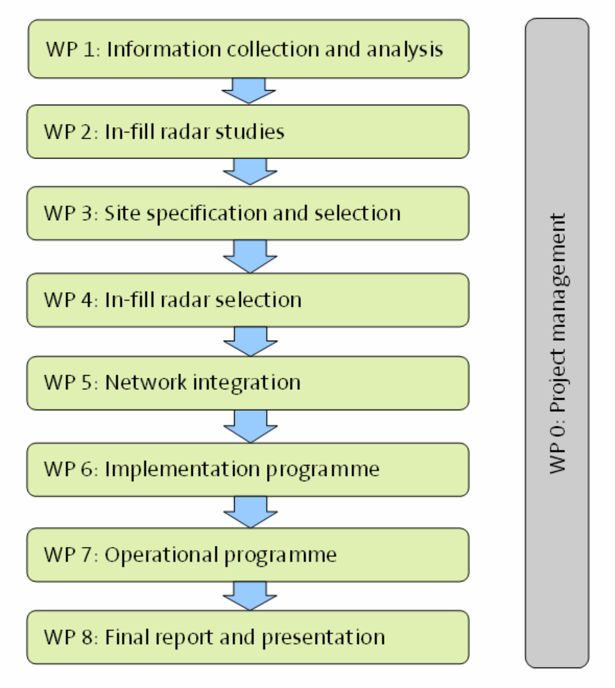


Figure 1: Study work packages

The study process was to collect relevant technical information (WP1), perform technical analysis on the radar interference problem (WP2), and perform an initial selection of possible locations for an in-fill radar (WP3). Radar suppliers were then approached and candidate radars that meet the technical requirement down-selected (WP4). The practicalities of integrating and bringing into service such an in-fill radar with existing MOD systems were addressed in co-operation with MOD (WP5 – WP7). Reporting of recommendations and conclusions is the final stage of the project (WP8); this is to include a presentation of conclusions to the wider community with interests in wind farm development.

# 3 Study findings

A summary of study findings by work package is presented below.

## 3.1 WP1: Information collection and analysis

### 3.1.1 Background

Relevant information relating to previous studies on the impact of wind turbines on MOD primary air surveillance radars was provided to QinetiQ and reviewed. This included:
- Material relating to experiments carried out by the Royal Air Force (RAF) on interference caused to air defence radars by wind farms;
- Technical information on RAF air surveillance radar characteristics.

For study purposes, QinetiQ was given access to relevant classified internal MOD reports and classified summaries of RAF radar characteristics.

There are two RAF-operated long-range air surveillance radars that are expected to be subject to interference from Round 2 Greater Wash wind farm developments: those at RRH Neatishead (Trimingham), Norfolk, and RRH Staxton Wold, North Yorkshire.

The current RAF Type 93 radars operating at these locations are due to for replacement in the near future. It is reported that MOD currently plans to install a new RAF Type 102 radar at RRH Neatishead, and a RAF Type 101 radar at RRH Staxton Wold [1]. However, it is understood that these plans may be subject to change.

It is known that the current Type 101 radar is particularly susceptible to interference from operating wind turbines within line-of-sight, resulting in a significant loss of radar capability above and in the surroundings of a wind farm.

### 3.1.2 MOD guidance on operational specification of a candidate in-fill radar

Guidance for study purposes was provided by the MOD in the form of an outline operational specification for the extent of performance recovery required of an in-fill radar, plus other supporting information [2].

In brief, the specification gave the following information.

- *Aim*: to reduce the impact of interference of wind farms to a minimum possible;
- *Target characteristics*: the in-fill radar is to be effective against a 1 $m^2$ Swerling 1 radar cross-section (RCS) subsonic aircraft capable of 9G acceleration;
- *Requirement (1)*: physical minimisation of "dead zones" created by wind turbines such that there is a high confidence (3 $\sigma$) that a track will be initiated between all dead zones;
- *Requirement (2)*: no impact [of windfarm interference] above 5 000 ft altitude in accordance with CAP 670 (Air Traffic Services Safety Requirements).

The following constraints were to apply for a potential in-fill radar:
- To be at Technology Readiness Level 8 or 9.
- Capable of being procured by Contracting For Availability (highly desirable).
- Radio frequency spectrum and planning permission must be feasible.
- Integration to existing UK Command and Control Systems UCCS and ACCS is to be assumed.

In addition, the in-fill radar was not required to add performance or coverage, only to recover lost capability.

Notwithstanding plans to site a Type 102 at Staxton Wold, for feasibility study purposes, QinetiQ was asked to assume that two Type 101 radars are used as Type 93 radar replacements. This was intended to examine the worse-case situation where, for example, for MOD operational reasons, a Type 102 radar earmarked for Trimingham is redeployed elsewhere.

### 3.1.3 Greater Wash Round 2 wind farm developments and interference to radars

The locations of Greater Wash offshore wind farm developments are shown in Figure 2. In addition to making use of public domain material, several wind farm developers provided information to QinetiQ concerning the possible layout and generic turbine designs to be employed in wind farms off the Greater Wash. It is understood that turbines generating 2 MW to 4 MW are most likely to be used offshore. The larger wind turbines typically comprise:

- A tower, 80 m in height, tapered from 5 m at the base to 2.5 m at the top;
- A nacelle, mounted on the top of the tower, which contains an electrical generator and turbine control system; and
- A three-bladed rotor, typically 120 m in diameter, that may rotate at between 8 and 20 revolutions per minute (rpm) and have a blade-tip speed of up to 100 m/s.

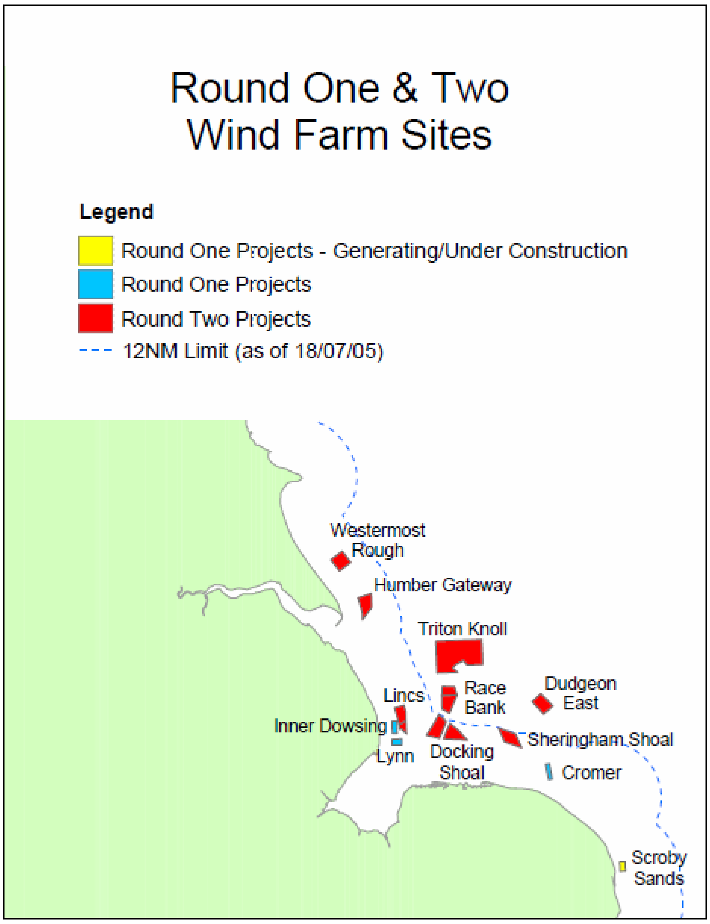


Figure 2: Locations of Greater Wash Round 1 and 2 offshore wind farm sites at 27 February 2007. The Round 1 site at Cromer is understood not now to be developed for engineering reasons. Derived from Crown Estate mapping [3].

At the present time, developers generally have neither decided on particular wind turbine types, nor determined exact turbine locations within their allocated Phase 1 or Phase 2 areas. It is understood that none of the developers are considering, so far as is known, turbines that exceed 150 m in blade-tip height above sea level. Plans generally show turbines being sited in rows and columns (often based on a triangular grid) with spacings of about 600 m to 1000 m between towers. Detailed layouts of turbines are likely to be dependent on local sea-bed surveys, and so will in practice vary from a regular grid.

The level of information received concerning wind farms was generic in nature except for the boundaries of the planned development locations.

Current air surveillance radars have a number of identified problems in coping with large wind turbines within their field of view. The most severe problem is coping with scattered signals from the rotating rotor blades. The blade motion imparts a Doppler-frequency shift on signals captured by the radar. Radars generally discriminate between wanted targets (such as aircraft) at low altitude, and unwanted targets, such as reflections from buildings, by virtue of the imparted Doppler frequency. The size of reflections from the blades are dependent on the orientation of the rotor. In general, a radar observes in time a combination of very large specular flashes from the leading and trailing edges of the rotor blades, plus a background of smaller echoes from other parts of the rotor and tower. A large proportion of reflections from the rotor are larger than those that are produced by an aircraft. False detections may therefore be produced that result in the radar reporting the presence of aircraft-like objects in the immediate vicinity of a wind farm, when, in fact, none are present. Depending on the design of the radar, data processing to suppress scattered signals from turbines may, conversely, result in the radar being desensitised to the presence of aircraft, suppressing detections of genuine air targets along with false detections from the turbine rotors.

It is expected that the two existing RAF radars will fall below their required capability level immediately above and around Phase 2 developments in the Greater Wash area. Since radars require line-of-sight to objects for detection, interference is expected to be caused only by those developments that are within line-of-sight of the radars. Estimated line-of-sight coverage areas from RAF RRH Staxton Wold and RAF RRH Neatishead (Trimingham) to objects at 150 m height above mean sea level are shown in Figure 3 for normal propagation conditions. It is seen that the Staxton Wold radar should only illuminate the two northern-most Phase 2 sites, Westermost Rough and Humber Gateway. The Trimingham radar is expected to illuminate many of the other Phase 2 sites. The irregular coverage patterns of the radars are caused by local terrain blockage.

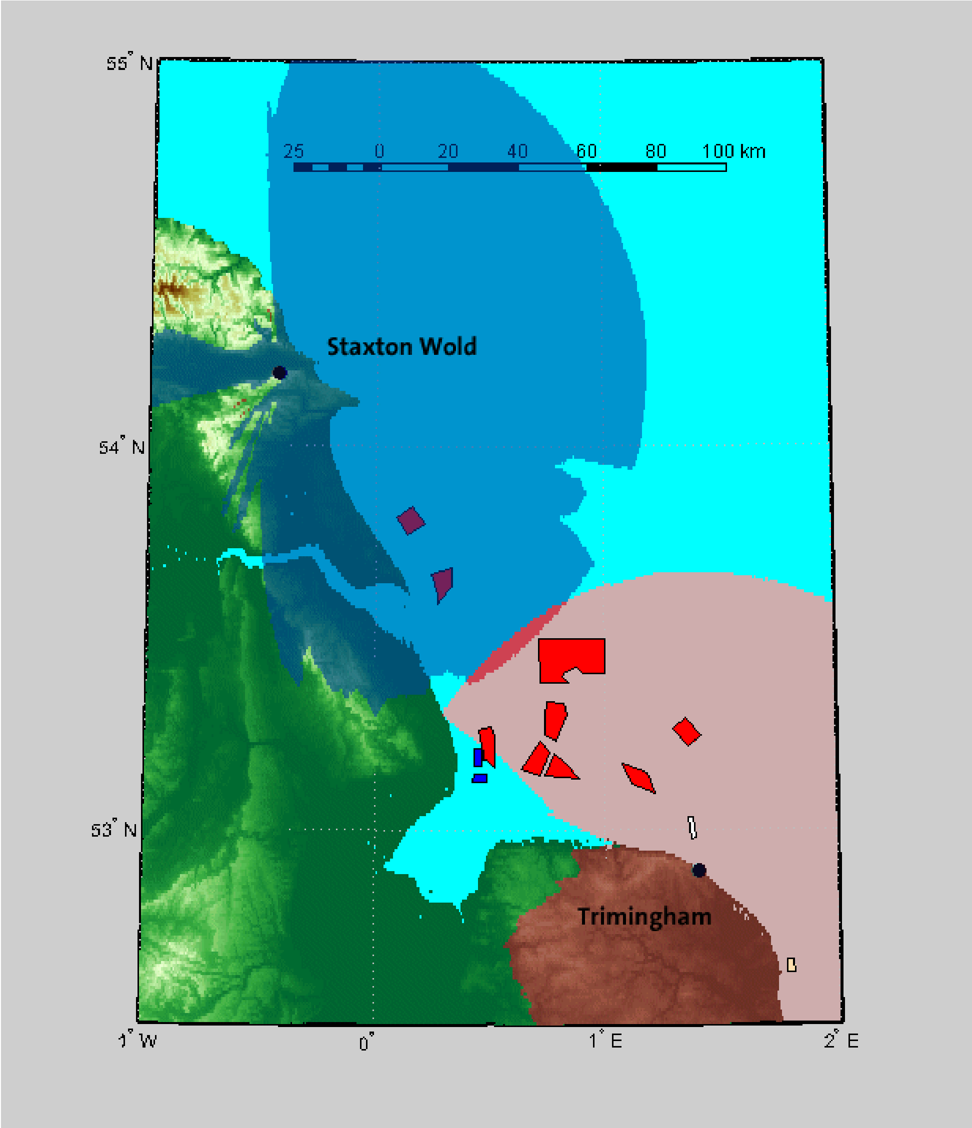


Figure 3: Line-of-sight area coverage from RAF RRH Staxton Wold (blue overlay) and RAF RRH Neatishead (Trimingham) (pink overlay) at 150 m above mean sea level in normal propagation conditions. The polygonal areas shown offshore are wind farm sites.

## 3.2 WP2: In-fill radar studies

Based on technical information collected in WP1, an analysis was made to understand (1) key technical factors that contribute to interference with radar operation, (2) potential features of an in-fill radar that would assist in mitigating the problem.

The key technical aspects are documented in the open literature. A particularly clear explanation of technical issues relating to interference is given in the document "The effect of windmill farms on military readiness" [4].

It is evident that to provide mitigation, an in-fill radar should have technical characteristics that minimise the generic problems associated with detection of aircraft in the presence of operating wind turbines.

A "Request For Information" (RFI) document was drawn up for circulation to radar manufacturers. A copy of the RFI as sent to radar manufacturers is shown in Appendix A to this report. It also includes a discussion of technical matters associated with wind farm induced interference with radars.

## 3.3 WP3: Site specification and selection

The low-altitude coverage of existing RAF radars in the Greater Wash area was modelled in relation to existing and proposed Phase 1 and Phase 2 wind farm developments. It was desired to identify a primary and secondary site to host an in-fill radar. Suitable land-based sites ideally need to be located at or near the coast, and local terrain must not impede significantly the low altitude coverage of the in-fill radar. Initial work focussed on existing MOD-owned land in the Greater Wash area. Consideration was also given to the existence of suitable infrastructure at MOD sites.

It was assumed that, primarily for through-life cost reasons, the in-fill radar would not be located offshore, although it would be technically possible to do so.

Therefore, for analysis purposes, it was assumed that the radar would be located onshore and mounted on a tower or other structure at a height of 12 m above local ground level. It is possible that another height could be selected depending on cost and any local planning constraints. Air Traffic Control radars are commonly mounted on towers 10 m to 20 m above ground level to improve coverage against low altitude targets.

The RAF operates coastal ranges in the Greater Wash area. Candidate sites include:

- RAF Wainfleet;
- RAF Donna Nook;
- RAF Holbeach.

Of these sites, propagation modelling showed that RAF Wainfleet has potentially suitable line-of-sight coverage: see Figure 4. It is understood that Wainfleet has modern site infrastructure and is in regular operation as an MOD range. It is noted that an in-fill radar having a detection range of up to 100 km slant-range would provide coverage down to at least 610 m (2000 ft) around and above all proposed Round 2 Greater Wash area wind farms. It would provide coverage down to 150 m over most of the wind farms in the central area off the Wash (see Figure 4).

RAF Donna Nook also has potentially suitable line-of-sight coverage (see Figure 5) but has poorer coverage compared to RAF Wainfleet for the more south-easterly wind farms. In particular, coverage does not extend down to 610 m above the Phase 1 wind farm at Scroby Sands, the most south-easterly of the Greater Wash sites. The site infrastructure at Donna Nook appears to be poorer than at Wainfleet.

RAF Holbeach is situated well within the Wash compared to the other sites, and provides inferior coverage over wind farms compared to Wainfleet and Donna Nook.

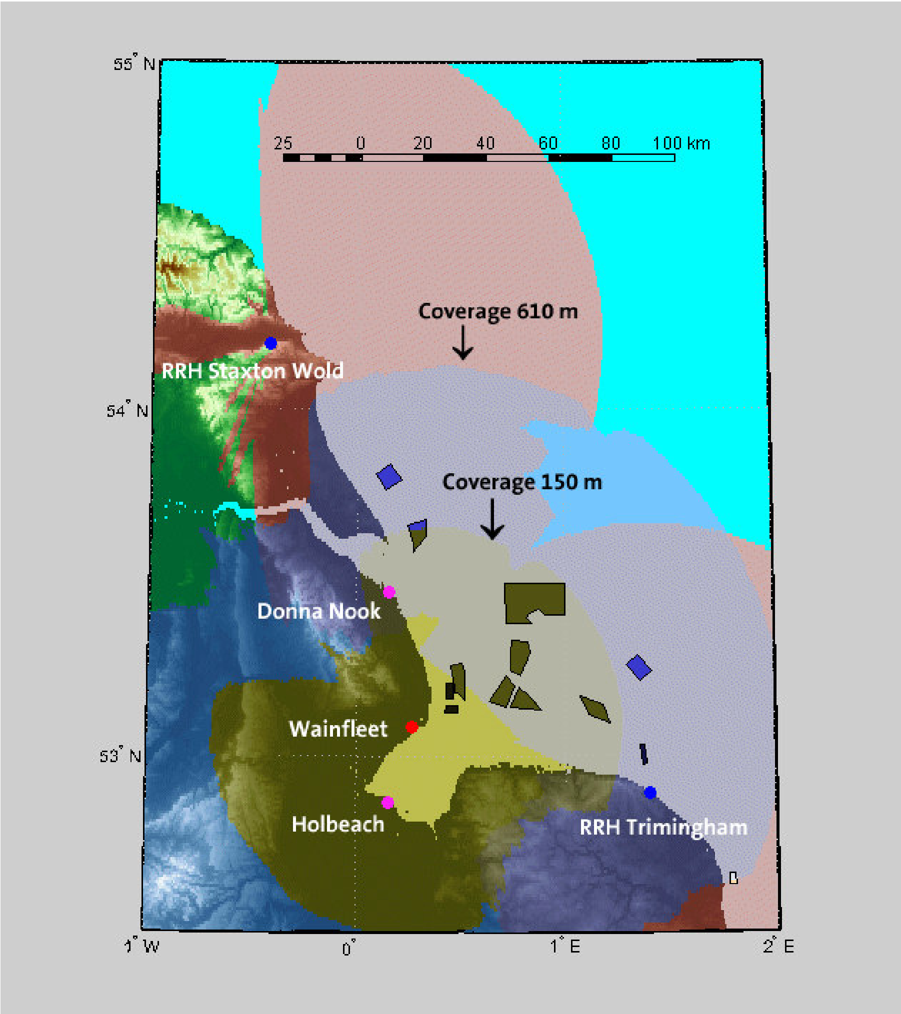


Figure 4: Example overlaid line-of-sight coverage areas from RRH Staxton Wold, RRH Trimingham, and a potential in-fill radar at RAF Wainfleet. Coverage areas from Wainfleet (arrowed) are shown for altitudes of 150 m (yellow) and 610 m (light blue). Coverage areas (pink) are also shown from Staxton Wold and Trimingham at 150 m altitude. The polygonal patches offshore are wind farm sites.

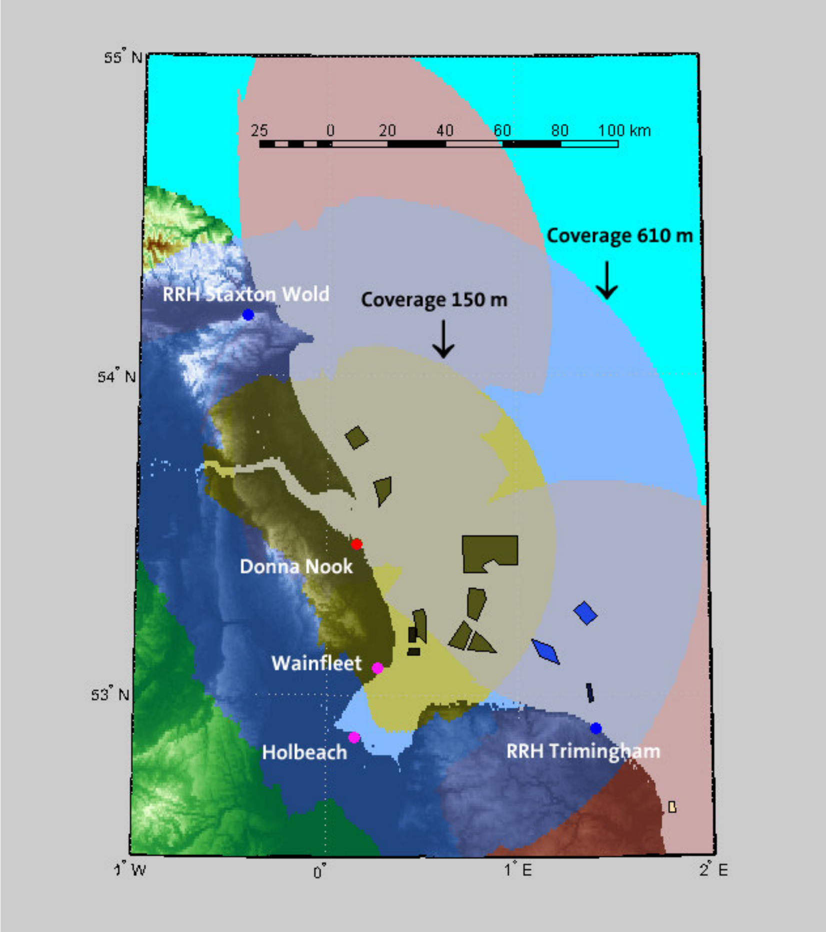


Figure 5: Example overlaid line-of-sight coverage areas from RRH Staxton Wold, RRH Neatishead (Trimingham), and a potential in-fill radar at RAF Donna Nook. Coverage areas from Donna Nook (arrowed) are shown for altitudes of 150 m (yellow) and 610 m (light blue). Coverage areas (pink) are also shown from Staxton Wold and Trimingham at 150 m altitude. The polygonal patches offshore are wind farm sites.

## 3.4 WP4: In-fill radar selection

### 3.4.1 Selection criteria

Criteria were formulated against which to assess the characteristics of potential in-fill radars. In attempting to distinguish wanted targets from other objects of no interest to a military radar operator, it is important to maximise the available information from the radar. Generically, this can be done by:

- Increasing the number of parameters measured by the radar;
- Improving the spatial resolution of the radar at plot level, and of associated ground-clutter maps used to detect tangentially-crossing targets;
- Improving the velocity resolution (if the radar is capable of unambiguous target velocity measurement);
- Improving the update rate on targets;
- Customised plot extraction and tracking algorithms for use in the vicinity of wind farms to control the impact of false-targets induced by the moving rotor blades;
- High instantaneous receiver dynamic range;

- Employment of a very low sidelobe antenna.

To meet Phase 2 wind farm planning and construction timescales, the study terms-of-reference directed that the in-fill radar must be available as a mature product that can be manufactured to order. A survey was therefore first undertaken of potential radars using public domain material produced by radar manufacturers, and in handbooks containing details of current military products such as those published by Jane's Information Group.

For commercial and military security reasons, detailed information about radar products is generally unavailable in the public domain. It was therefore necessary to approach radar manufacturers to seek sufficient technical information to assess the viability of a solution.

### 3.4.2 Request For Information

A formal "Request For Information" was issued by QinetiQ to selected radar manufacturers that were considered to have radar products with suitable characteristics. The manufacturers approached were selected and approached in cooperation with MOD stakeholders.

Of the radar manufacturers initially approached, positive responses were received from five potential suppliers. BAE Systems Insyte declined to participate in the in-fill radar study for commercial reasons. No reply was received from two other major radar manufacturers.

The technical responses differed in the level of information provided, and in two cases, multiple potential solutions were offered. Without exception, detailed information was only released to QinetiQ for study purposes on an "in-confidence" basis, generally under legally-binding non-disclosure agreements. It is therefore possible only to outline in this open report the various proposed solutions. Detailed technical responses from radar manufacturers has, for reporting purposes, had to be confined to limited circulation annexes to this report.

The responses received are summarised in Table 1 below.

| **Manufacturer** | **In-fill solution** |
|---|---|
| SELEX Systemi Integrati (UK) Ltd | Multiple options, listed according to assessed technical risk and cost.<br>(1) Data fusion of detections from other radars.<br>(2) Redeploy Watchman as in-fill radar.<br>(3) ATCR-33S with dish antenna as in-fill radar.<br>(4) ATCR-33S with phased array antenna as in-fill radar.<br>(5) ARGOS-45 phased array radar as in-fill radar.<br>(6) RAT-31 as in-fill radar. |
| Lockheed Martin Company (Maritime Systems and Sensors) USA | TPS-77 radar |
| Lockheed Martin Company (Information Systems and Global Services) USA | "SILENT SENTRY" passive coherent location sensor as in-fill radar. |
| Saab Microwave Systems (Sweden) | GIRAFFE AMB radar. |
| Thales Group | (1) "Homeland Alerter 100" passive coherent location sensor as in-fill radar.<br>(2) MASTER 3D as in-fill radar. |
| BAE Systems Insyte | Declined to participate in the study. |

Table 1: Responses from manufacturers and summary of solutions

### 3.4.3 SELEX Sistemi Integrati UK Ltd – details of response

SELEX-SI UK Ltd is a subsidiary of the Finmeccanica Company and is a major supplier of Air Traffic Control (ATC) radars and systems to both civil and military users. SELEX-SI has previous experience of radar interaction with wind farms in relation to its ATC radar business, and it has participated in UK MOD trials examining the impact of wind turbines on its military ATC products. Multiple potential solutions were suggested and ordered in terms of practicality, technical risk and estimated cost. The following potential options are edited from written material provided by SELEX-SI UK Ltd to QinetiQ.

**SELEX-SI Option 1**

Use an existing 2-D ATC radar system or systems in the vicinity of the proposed wind farms as "in fill" or "in fills". The more radar systems that are employed in a dispersed manner, the greater the likely level of recovery of capability for the MOD air defence radars. The radar systems employed will need to be upgraded with the SELEX SI Ltd SPE-3000. There are Watchman radar systems in service with the RAF that may, subject to coverage modelling, be able to contribute to the in-fill process: these systems are at RAF Marham, Cottesmore, Coningsby and Waddington. In addition, there are similar Watchman radar systems at Humberside International Airport and further north at Durham Tees Valley Airport that can be upgraded and integrated. The SPE-3000 uses and improves existing capability, and also extends the life of the Watchman radar system by 15 years.

This is the lowest-risk robust solution with the capability to add extra sensors as wind farm deployment develops. There are many Watchman systems in service across the UK. Support is available at the parent radar airfields and via AOSIPT both of whom in turn use SELEX SI Ltd as the Post Design Services Authority. SELEX SI Ltd is planning to continue to support the Watchman out to 2026 and is willing to enter into discussions as to the provision of a Technical Services Contract for the parent system or systems and the upgrade.

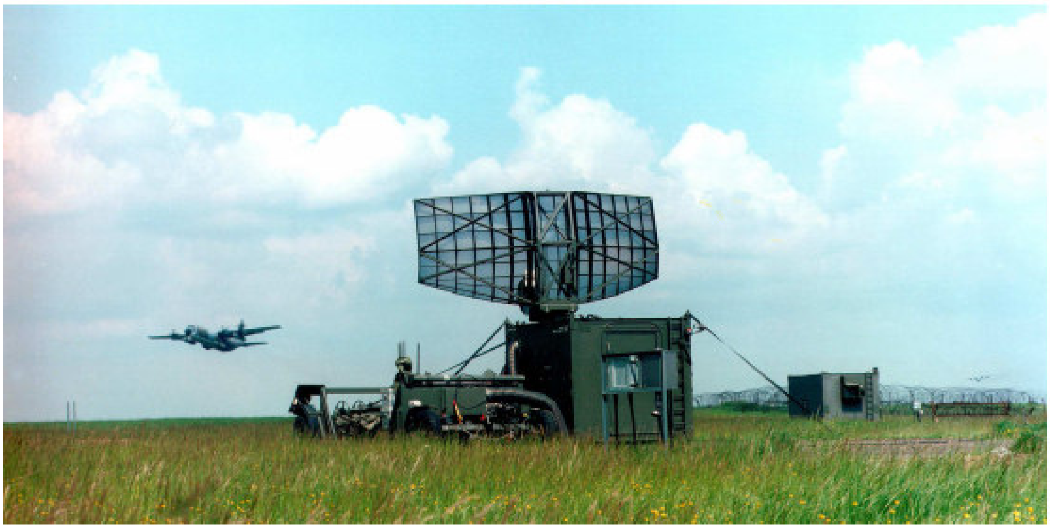

Figure 6: SELEX Watchman radar (image courtesy of SELEX-SI Ltd).

The Watchman radar at Cromer has been replaced by a Raytheon ASR10SS and this is physically well placed for in-fill use. To mitigate wind farm interference, it is recommended that the ASR10SS is interfaced to an SPE-3000 processor. An SPE-3000 upgrade is capable of being applied to the ASR10SS but will attract some one-off engineering costs due to the differences in the interfaces. For this one site the risk, cost and delivery are somewhat higher than the standard Watchman.

**SELEX-SI Option 2**

Use existing Watchman radar system(s) that are surplus to requirements at other MOD sites and re-deploy to MOD sites such as RAF Wainfleet or, if necessary, other available sites such as RAF Donna Nook or Holbeach. The system or systems will need upgrading using the SELEX SI Ltd SPE-3000 that will enter service with the MOD in the near to medium term. It therefore uses and improves existing capability together with extending the life by 15 years. This is another low risk robust solution with the capability to add extra sensors as wind farm deployment develops. It is anticipated that a significant number of MOD-owned Watchman radar systems will become available due to RAF re-organisation. Support is available to MOD via the AOSIPT, which, in turn uses SELEX SI Ltd as the Post Design Services Authority. SELEX SI Ltd is planning to continue to support the Watchman radar out to 2026 and is willing to enter into discussions as to the provision of a Technical Services Contract for the parent system or systems and the upgrade.

For either Options 1 or 2, if it were deemed necessary to use multiple in-fill radar systems, SELEX-SI would propose the use of a "Sensor Gateway" to provide a single SDO1000 plot stream to the MOD end user.

**SELEX-SI Option 3**

Deploy a new 2-D radar to RAF Wainfleet and if necessary further radars to other available sites; the arguments discussed in Options 1 and 2 above generally apply to this solution. For this option, SELEX SI Ltd recommends the ATCR-33S DPC with a conventional modified-cosecant[2] antenna. This system will enter service in the UK in the near and medium terms and is proven at a number of sites world wide. This is a lower risk robust solution than Option 4 below, with the capability to add extra sensors as the wind farm developments expand and has lower costs than Option 4.

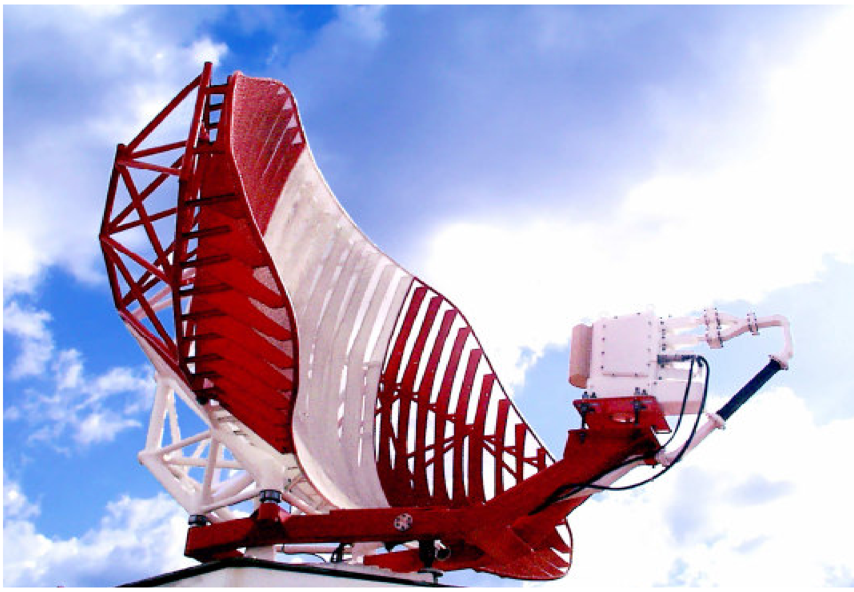

Figure 7: Conventional antenna for SELEX ATCR-33S radar (image courtesy of SELEX-SI Ltd).

**SELEX-SI Option 4**

Deploy a new 2-D radar at RAF Wainfleet and if necessary further radars at other available sites; the arguments discussed in Options 1 and 2 above also generally apply to this solution. SELEX-SI Ltd recommends the ATCR-33S DPC with the proven phased array antenna. This is an elegant solution using a Commercial-Off-The-Shelf product that is in operational service. The phased array antenna has lower sidelobes and using the receiver beam forming network there is the potential to exploit this selectively on receive to provide beam nulls around wind turbines.

This is a medium technical risk robust solution with the capability to add extra sensors as the wind farm deployment develops however it will attract higher costs than Options 1, 2 and 3.

Figure 8: SELEX SI ATCR-33S radar with phased array antenna. (Upper antenna is for an associated secondary surveillance radar.). Image courtesy of SELEX-SI Ltd.

Figure 9: SELEX S-Band solid state transmitter for conventional and phased array antennas. (Images courtesy of SELEX-SI Ltd).

**SELEX-SI Option 5**

Deploy a new SELEX ARGOS-45 C-Band (5.4 GHz to 5.9 GHz) phased array radar at RAF Wainfleet and if necessary other available sites. This would be a higher technical risk solution as there is far less trials work on the effects of wind farms at this frequency. The higher frequency allows narrower and well formed beams that will have some inherent ability to "look" just above the wind farms and not fully illuminate the blades. This is largely unproven so the risks are higher. Again there is the capability to add extra sensors as the Wind Farm deployment develops but higher costs than for Options 1 through 4 above.

Figure 10: SELEX ARGOS-45 C-band radar in road transportable configuration (image courtesy of SELEX-SI Ltd).

**SELEX-SI Option 6**

Deploy a new 3D phased array radar at Wainfleet and, if necessary, other available sites. A medium risk and elegant solution that is very probably over compliant and will attract much higher capital and through life costs than Options 1 through 5 above. SELEX SI Ltd recommends the proven RAT-31, effectively the *de facto* standard NATO Long Range 3D Radar.

Figure 11: SELEX RAT-31 long-range air defence 3-D radar and associated SSR antenna (image courtesy of SELEX-SI Ltd).

### 3.4.4 Lockheed Martin Maritime Systems and Sensors – details of response

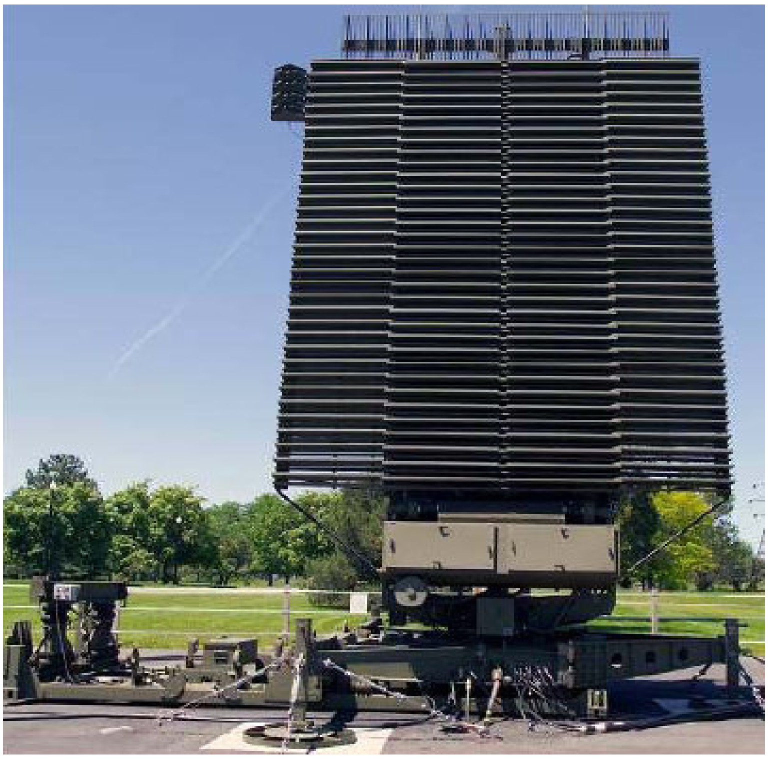

Figure 12: Lockheed Martin TPS-77 3-D air defence radar. The smaller antenna on top of the main antenna is for a collocated SSR.

The Lockheed Martin Company is a major US supplier of defence equipment and technology services. The Maritime Systems and Sensors business unit specialises in defence and security systems, including radars. The TPS-77 is a long-range 3-D air surveillance radar that operates at L-band (1.3 GHz) frequency band. The radar is the latest version of a radar design that was first manufactured in the 1980s and has been continuously updated. The UK RAF has two derivatives of the TPS-77 radar in current service, designated the RAF Type 92.

The TPS-77 radar has recently (April 2007) participated in a trial to examine its capabilities to detect a small, slow and low-flying aircraft over a wind farm in the USA. Details of trials results have been provided to QinetiQ in which both radial and tangentially-crossing over flights at altitudes between 1 000 ft and 10 000 ft above ground level. Taken at face value, the trials results indicate the radar maintained its target detection performance well at all altitudes above the wind farm, with a small increase in false alarm rate due to turbine-induced clutter. It was considered that some further optimisation of the radar set-up could be performed to reduce the occurrence of false tracks.

### 3.4.5 Lockheed Martin Information Systems and Global Services – details of response

A second offering from the Lockheed Martin Company was that of the SILENT SENTRY passive coherent location system. This is a novel form of radar-like sensor that does not use a conventional radar transmitter. It is effectively "receive only" in that it exploits FM-radio transmissions that are already present in the environment from civil broadcasters, such as the BBC and independent radio stations. Aircraft scatter FM-radio signals and these can be picked up by a suitable receiver and processed to measure the position and velocity of the aircraft target. The description below is derived from open literature material [5].

Silent Sentry's Passive Coherent Location (PCL) technology provides precise, real-time, all-weather detection and tracking ideal for air surveillance, and national resilience applications. Silent Sentry's innovative approach is totally passive, allowing targets to be tracked without generating any RF energy by using existing broadcast signals from FM radio transmitters. The system has no RF safety or environmental impact. With no moving parts and a commercial off-the-shelf (COTS) approach, Silent Sentry is less expensive to acquire, operate and maintain than traditional radar systems.

Silent Sentry provides robust performance featuring three-dimensional tracking with highly accurate horizontal position and velocity measurements. A modular, flexible, network-ready COTS design facilitates integration with legacy and emerging systems. Silent Sentry systems are compact, easily deployed, and configurable for a variety of surveillance applications.

Figure 13: Lockheed Martin SILENT SENTRY passive coherent location sensor (image courtesy of Lockheed Martin).

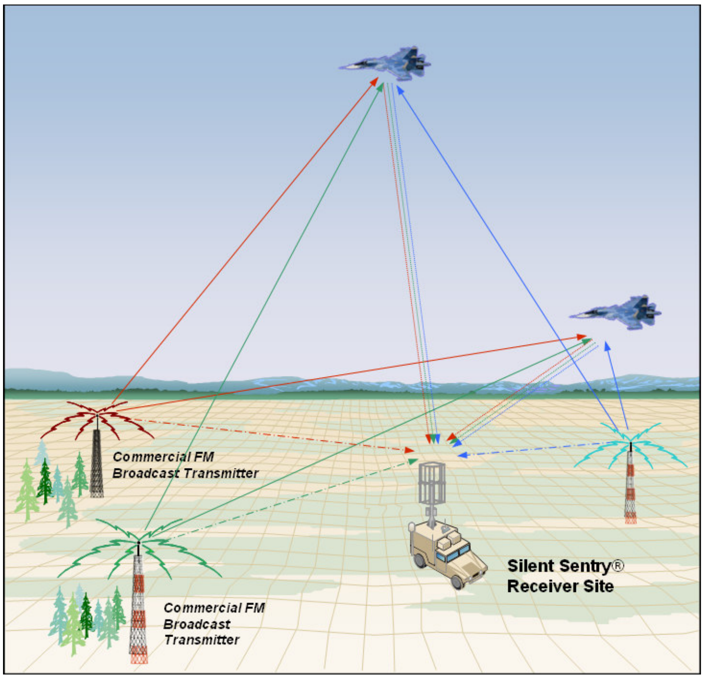


Figure 14: Principles of operation when exploiting scattered signals from FM broadcast transmitters. The Silent Sentry receiver compares the scattered radio waves to the direct signals to determine the location and velocity of the target (image courtesy of Lockheed Martin).

It is noted that the performance of a Silent Sentry systems for Greater Wash in-fill purposes is dependent on the relative locations and characteristics of the broadcast radio transmitters in the Greater Wash area. The system offered for the Greater Wash in-fill use is understood to be an FM-radio only based sensor.

| **Performance summary** | **Parameter** |
|---|---|
| Surveillance volume | Azimuth: up to 360°<br>Elevation: 60°<br>Continuous search, Update rate once per second. |
| Range | Typically 0 to 150 nautical miles within antenna field of view<br>Depends on antenna used |
| Targets | 100+ simultaneously |
| Accuracy (FM) | 150 m horizontal position<br>1000 m vertical position<br>< 2 m/s horizontal velocity |
| Data output | Silent Sentry track format or OTH Gold, others available |
| Configurations | Installation on fixed or mobile platforms |
| Form factor | VME rack<br>2' x 2' transit cases<br>Easy to ship or transport |
| Operating environment | Room temperature<br>Shelter protected<br>1.5 kW mains power |

Table 2: Summary of Silent Sentry typical performance, derived from open literature product brochure [5].

### 3.4.6 Saab Microwave Systems – details of response

The GIRAFFE Agile Multi Beam (AMB) radar is proposed as an in-fill radar. The Giraffe AMB radar (see Figure 15) operates at C-band (5.4 – 5.9 GHz) and is designed to detect and track low altitude air targets out to the radio horizon, typically 40 km.

Figure 15: Saab GIRAFFE AMB radar, in truck-mounted mobile configuration [6].

GIRAFFE AMB is manufactured by Saab Microwave Systems of Sweden, and is in service with the Swedish armed forces. Examples have also been delivered to the armed forces of the USA and France [6].

It is designed to operate with high levels of surface clutter and in the presence of electronic countermeasures and has:

- Low antenna sidelobes;
- Frequency agility;
- Digital pulse compression;
- Pulse Doppler processing modes.

The transmitter signal processor and operator consoles can be housed in a 20 ft ISO container. The antenna comprises a digital array with a fan-shaped transmit beam in elevation and multiple simultaneous receiver beams with monopulse function. The instrumented range of the radar is operator selectable at either 30 km, 60 km or 100 km. Coverage is up to 20 km (> 70°) in elevation. The antenna is supported on a scissors-mount platform elevated to 12 m. The antenna rotates at up to 60 rpm (operating mode dependent). The antenna is 2.0 m wide by 1.1 m tall [7].

QinetiQ has been provided with further, limited-distribution details of the capabilities of the GIRAFFE AMB radar, together with a discussion by Saab Microwave Systems of radar operation in the presence of interference from a wind farm.

### 3.4.7 Thales Group – details of response

Thales Air Operations, on behalf of Thales Group, offered only preliminary information relating to the Thales "Homeland Alerter 100" product for potential in-fill radar use. Details of this system are not publicly releasable and are given in the limited-distribution Annex A to this report.

In addition, Thales Air Operations highlighted the MASTER 3D long range air defence radar as a potential in-fill radar, noting that it has sophisticated Doppler processing modes available. It was remarked, however, that the MASTER 3D radar is oversized in terms of range coverage relative to the Greater Wash in-fill radar requirement.

## 3.5 WP4: Discussion of potential in-fill radar solutions

### 3.5.1 Introduction

This subsection of the report gives an analysis by QinetiQ of the proposed in-fill radar solutions and how well they are likely to meet the MOD user requirement.

A direct comparison of proposed solutions has been difficult to achieve as the level of detail provided by the different radar manufacturers differed widely.

The assessment of responses was performed primarily against the outline MOD user requirements for interference mitigation, outlined in section 3.1.2 above. A subjective assessment was also made of the general level of understanding of the technical problem evident in the responses and the extent to which previous work had been undertaken in mitigating wind farm interference. Due regard was also made of any supporting evidence in the form of experimental demonstrations of the validity of proposed in-fill solution(s) through observations of trials aircraft flying in the vicinity of operating wind farms.

### 3.5.2 Analysis of alternatives

The proposed in-fill radar solutions notified to QinetiQ are assessed in **Table 3**.

| Manufacturer | In-fill solution assessment |
|---|---|
| SELEX-SI (1)<br>Data fusion of detections from other existing radars using SPE-3000 processors. | No new in-fill radar required so lower cost. Needs data fusion processing upgrades to existing 2-D radars. Needs further work to establish level of altitude coverage and numbers of radars needed to contribute. 2-D coverage mitigation only. Uncertainty about level of mitigation achievable currently. |
| SELEX-SI (2)<br>Redeploy Watchman with SPE-3000 as in-fill radar. | Re-uses existing radar from inventory to reduce costs, installed at coastal site. Requires data processor upgrade. 2-D coverage mitigation. Some uncertainty about level of mitigation achievable currently. Some independent trials data available. |
| SELEX-SI (3)<br>ATCR-33S with dish antenna as in-fill radar. | New 2-D radar, low-medium cost. 2-D coverage mitigation. Some uncertainty about level of mitigation achievable. |

| | |
|---|---|
| SELEX-SI (4)<br>ATCR-33S with phased array antenna as in-fill radar. | New 2-D radar employing phased array antenna. Higher cost than Option (3), but potentially higher performance. Some uncertainty about level of mitigation achievable. |
| SELEX-SI (5)<br>ARGOS-45 phased array radar as in-fill radar. | Candidate but limited data provided for assessment purposes. Probably medium-to-high cost. Standard product has limited range at 45 km. |
| SELEX-SI (6)<br>RAT-31 as in-fill radar. | Candidate but probable high cost. Radar range greatly exceeds Greater Wash in-fill needs. |
| Lockheed Martin MS2<br>TPS-77 radar as in-fill radar. | Good performance in a recent onshore wind farm trial. Likely to be high cost to acquire. Radar range greatly exceeds Greater Wash in-fill needs. Some further optimisation possible. |
| Lockheed Martin IS&GS<br>SILENT SENTRY passive coherent location sensor as in-fill radar. | Novel solution but dependent on radio station coverage. Medium cost. Uncertainty over level of mitigation achievable. |
| Saab Microwave Systems<br>GIRAFFE AMB radar | Radar range is matched to the required Greater Wash in-fill needs. Medium to high cost. Some uncertainty over level of mitigation achievable. A 3-D mitigation solution. |
| Thales Group (1)<br>"Homeland Alerter 100" sensor product as in-fill radar. | Potentially novel solution, low to medium cost. Insufficient knowledge of product to comment on level of mitigation achievable. |
| Thales Group (2)<br>MASTER 3D as in-fill radar. | Insufficient detail provided on product to comment on level of mitigation achievable. Potentially high cost. |

Table 3: QinetiQ assessment of in-fill radar alternatives.

## 3.6 WP5: Network integration

The current UK air surveillance and interceptor command and control system (UCCS) was developed for the UK MOD by IBM UK Ltd. A brief, open literature overview of the system is available in the form of a case study [8].

The feasibility of integrating an in-fill radar into the UK Air Command and Control System was examined through discussions with IBM UK Ltd. It was established that MOD systems, and in particular the automated air target tracking and data fusion system used by the RAF can be configured to support the addition of an in-fill radar for use in the Greater Wash. Only relatively minor changes should be necessary to integrate an in-fill radar [9], likely to be small in cost relative to the cost of procuring an in-fill radar. Where a possible in-fill solution involves multiple radar sensors, some lower-tier integration of radar sensors may be desirable prior to networking into UCCS. This may be achieved using an additional COTS product, such as the Sensis Corporation's "Sensor Communications Gateway" [10].

## 3.7 WP6: Implementation programme

The suggested way ahead could consider:

- Inclusion of additional mature radars in planned UK radar trials programmes to gather positive evidence as to their wind farm mitigation performance. In particular, it would be of interest to try to gather data from a high-TRL medium-range 3-D radar that is well matched to the ranges required for the Round 2 wind farm developments. Two manufacturers expressed an interest to QinetiQ in gathering data in UK trials activities to help optimise their products.
- A potential competition between selected candidate in-fill radar suppliers to secure best value for money.
- Procurement via "Contracting For Availability".
- Procurement to be managed by MOD Defence Equipment and Support (DE&S). Although other routes for in-fill radar procurement might be used, given the need to integrate an in-fill solution with other MOD systems, procurement would seem most appropriate through DE&S.
- It is considered that minimum timescales for procurement to order is approximately 18 months.

## 3.8 WP7: Operational programme

The potential in-fill radar solutions are capable of a high level of automation, and suppliers have indicated that contractor-provided support and equipment maintenance can be provided on a "24 x 7" basis within a service contract. Assuming that procurement is made on a "Contracting For Availability" basis, the impact on MOD operations and required personnel levels is assessed as being very low.

If integrated with existing MOD networks, such that automated tracking is performed with very low false-track initiation rates, the impact on MOD radar operators should also be very small.

# 4 Conclusions

Future Round 2 offshore wind farm developments in the Greater Wash area of the United Kingdom have the potential to cause an unacceptable level of interference to primary air surveillance radars operated by the Ministry of Defence (MOD) at Trimingham and Staxton Wold. Such a loss of radar capability is anticipated to result in planning objections and a delay to the consents required by developers for the construction of Round 2 wind farms and potential future offshore sites.

This study was commissioned to examine the feasibility of deploying a new radar in the Greater Wash area to provide extra observations around and above offshore wind farms. The new radar would "in-fill" regions of air space where surveillance coverage is predicted to be lost due to interference caused by offshore wind turbines.

The terms of reference were to:

- Clarify MOD requirements concerning air surveillance radar performance in the Greater Wash area;
- Examine how an "in-fill" radar might be used to address the problem, and identify technical uncertainties relating to the effectiveness of such a solution;
- Examine and recommend candidate sites for deployment of an in-fill radar;
- Specify and identify a candidate radar or radars that meet the assumed in-fill requirement, for further assessment and possible procurement;
- Determine how an in-fill radar can be integrated with the existing MOD air surveillance network and define an implementation plan.

Following inputs on radar user requirements and receipt of background information from the MOD, a set of technical features for a candidate in-fill radar were drawn up by QinetiQ, and a number of radar manufacturers were then approached with a formal request for information. Positive responses were received from five radar manufacturers, who supplied information to QinetiQ on candidate in-fill radar solutions.

The proposed solutions differ in terms of technology employed, the level of detail provided, and product maturity; some companies also provided more than one possible solution. Where possible the results of radar trials involving real equipment observing real aircraft above wind farms were sought and evaluated.

On the basis of technical material received, it is judged that:

- There is no identified off-the-shelf in-fill radar that can fully recover lost capability above Greater Wash Round 2 wind farms.
- The degree of capability loss can, however, be substantially reduced by introduction of an in-fill radar, either in the form of adding a new radar or possibly making use of existing radars.
- Preferred sites for an in-fill radar are Crown owned land on the east coast. Land at the MOD range at RAF Wainfleet is the first choice, on the basis that it provides better coverage over the more southerly Round 2 sites. RAF Donna Nook was identified as a secondary option. Some more detailed investigation is required to identify planning constraints.
- Credible potential solutions in the form of mature products have been advised by two radar manufacturers that would significantly improve the worst-case baseline situation in which two RAF Type 101 radars are in operation at RRH Staxton Wold and Neatishead.
- It is assessed that the Lockheed Martin TPS-77 3-D radar would provide a significant level of mitigation if sited, for example at Wainfleet. A disadvantage of this solution is its likely high procurement cost and required level of through-life support cost.
- It is assessed that one of the identified in-fill solution options by SELEX SI Ltd involving either an upgraded Watchman or a new ATCR-33S radar may have merit for in-fill radar

use. These are likely to incur lower costs than a 3-D radar but offer a lower level of wind farm interference mitigation.

- Other radar solutions have been submitted but are less mature and would require more detailed analysis and ideally trials activities to reduce technical risk. Some may, however, be able to act in an in-fill radar role.
- Data-fusion is a key technology to improve the probability of target detection and reduce false alarms; such technology is relatively mature and some is already in service with the MOD. Some enhancements are likely to industry products that may improve in-fill radar performance and these may be able to increase the level of mitigation as algorithms develop. Progress in this area should be closely monitored.
- It is noted that overlapping coverage from primary radars in the region; e.g. Staxton Wold and Neatishead (Trimingham) provides mutual coverage against targets at altitudes above a few thousand feet. The loss of coverage caused to an individual air defence radar is therefore already capable of mitigation in existing MOD systems. The contribution of an in-fill radar is therefore primarily at low target altitudes.
- Current MOD radar command and control systems are understood to be able to accept plot-level input from a correctly specified new in-fill radar. It is understood that integration with automated tracking systems can be performed with only minor hardware issues.
- The selection of a preferred in-fill solution is a matter of performing a trade-off between capability recovery, cost and technical risk.

# 5 Recommendations

- MOD should refine further its User Requirements relating to air defence radar coverage in the vicinity of new wind farms, and define a process to assess the level of mitigation required and what trade-offs can be made. It is necessary for clarity to be secured in this matter at senior levels within the MOD. It is noted that a review of Air Traffic Services safety cases is being pursued by stakeholders with BERR (formerly DTI) sponsorship, and this should be taken into account by MOD when complete.
- Further analysis is necessary to perform trade-offs between the most promising options highlighted in this study. The most mature technical solutions given to the study differ in cost and technical performance. Consequently, there is a cost-benefit analysis to be done in terms of the level of mitigation provided.
- RAF Wainfleet is the preferred site for locating a new in-fill radar, and Defence Estates should investigate options for siting a new radar at this location and if deemed necessary, apply for planning permission.

# 6 List of data sources


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# Appendix A

# REQUEST FOR INFORMATION

**In-fill radar for mitigation of the effects of offshore wind farms on primary radars**

## 1 Background

A number of offshore wind farms for electricity production are planned around the coastline of the United Kingdom. Unfortunately, due to their large size and rotating wind turbines, some ground-based 3-D air surveillance radars within line-of-sight of these wind farms are expected to be subject to interference. A potential method of reducing the effect of large wind turbines on existing radars is to deploy an additional radar to help to mitigate the interference experienced. This Request For Information seeks to identify a possible "in-fill" air surveillance radar that would provide additional coverage against air targets in the vicinity of off-shore wind farms, primarily at target altitudes between zero and 5000 ft above mean sea level, to permit existing radars to continue to operate, possibly without modification.

## 2 Information required

QinetiQ requests technical information concerning radar products that may be able to meet the requirement outlined for an in-fill radar to operate with other UK Government-owned primary 3-D air surveillance radars.

The technical information should include sufficient detail to demonstrate that the radar product is able to meet an outline user requirement (see section 3 below) for reducing the impact of interference from offshore wind farms. A discussion of radar technical parameters is included in this document.

If it is not possible to meet the technical requirement with a current production radar, discussions would be welcomed as to how this might be achievable by modifying a current radar design.

This document does not constitute a commercial offer of a contract and is sent without commitment.

## 3 Outline user requirement

### 3.1 Aim

Reduce impact of interference of wind farms on primary 3-D air surveillance radars to a minimum.

### 3.2 Air target characteristics

1 $m^2$ radar cross-section (RCS) having Swerling 1 fluctuation statistics, capable of 9 G acceleration.

### 3.3 Coverage requirements

Minimisation of the "dead zone" (i.e. a region where loss of detection of the defined air target occurs) around wind turbines such that there is a high degree of confidence (3 sigma) that a track can be initiated during the time period that a target is between dead zones and is thus visible to a radar.

No impact on existing radar coverage above 5 000 ft in the vicinity of wind farms.

### 3.4 Constraints

The in-fill radar is to be at Technology Readiness Level (TRL) 8 or 9. TRL 8 means "The technology has been proven to work in its final form and under expected conditions." TRL 9 means "The technology is in final form and applied under mission conditions, such as are encountered in either operational test and evaluation or in actual operational mission conditions".

It must be feasible to obtain a licence within the UK to transmit Radio Frequency (RF) signals at the frequencies and powers required by the in-fill radar.

The radar is to be capable of integration at plot level with existing UK and NATO air surveillance command and control systems.

### 3.5 Interpretation

The in-fill radar is to provide principally coverage against low altitude targets in the vicinity of off-shore wind farms. It is likely to have overlapping coverage with one or more existing 3-D primary air surveillance radars. Mitigation of the effects of wind farms is to be measured after data fusion of in-fill radar outputs with those of other radars.

The key performance issue is mitigation of the lost coverage due to the wind farms. It is not required to provide additional air surveillance coverage that would exceed that provided by the existing primary radars in the absence of wind farms.

Mitigation is required only against wind farms within line-of-sight (LOS) of existing radars. The desired detection range of the in-fill radar is 100 km or greater against the specified air target. This is required to provide sufficient coverage above offshore wind farms that may be 100 km distant from the in-fill radar but within LOS distance of an existing radar at a different location. Potential in-fill radars with a range less than 100 km may be considered if they have significant technical capabilities.

The in-fill radar is not required to be fitted with a secondary surveillance radar interrogator or receiving system.

The in-fill radar may be assumed to be physically located at or next to a coast-line, overlooking the sea. Ground level at the site is likely to be 3 m to 8 m above mean sea level. A prepared site with road access may be assumed. Prime power (50 Hz 3-phase mains electricity supply) may be assumed to be available.

## 4 Characteristics of offshore wind farms

The proposed turbines are expected to be physically large, comprising:

1. A tower of metal tubular construction, typically 5 m in diameter at the base to 2.5 m diameter at the top. The tower is typically 80 m tall at the rotor hub.

2. A rotor, fitted typically with 3 blades. The rotor diameter may be up to 90 m. The maximum rotor tip height above sea-level may be up to 150 m. The rotor turns at between 8 and 20 revolutions per minute (rpm), typically 13 rpm. The rotor tip may reach speeds of up to 100 m/s. The pitch of the blades is adjusted automatically, according to the wind-speed. The blade is typically constructed of epoxy- resin and fibreglass, often incorporating a metal core and metal tips. Although not highly electrically conducting, the blade composition has a relatively high electrical permittivity and so reflects RF energy quite well.

3. A nacelle containing the electrical generator and other equipment. The nacelle and rotor are turned (yawed) into the wind. The rotation axis of the blades is therefore dependent on the

wind direction. The nacelle may have flat sides and produce a large specular return to the radar in some orientations.

In addition, it is likely that a wind farm may comprise approximately 100 turbines, separated by about 200 m to 1000 m. A typical wind farm might be 3 km x 10 km in size, in which the turbines are ordered in an array based on a triangular unit cell. Some planned wind farms may be, however, larger than this.

It should be noted that off-shore wind farms are likely to use larger turbines than are currently used on-shore. The typical expected power output of a turbine to be used offshore is 2 MW to 3 MW. Further information on wind farm turbines and their radar scattering characteristics can be found in reference [1] and further general information at [2].

## 5 Expected interference from wind farms

Interference is likely to be experienced principally in radar antenna elevation beams that illuminate the wind turbines (e.g. the two lowest elevation beams). Interference is also possible into sidelobes of higher elevation beams. The forms of interference may include one or more of the following. (Note that the listing of a potential problem here should not necessarily be construed as indicating it is also present in any UK 3-D surveillance radar that may be affected by interference from wind turbines.)

1. A large, discrete radar return from the tower and nacelle. Depending on the engineering design, the turbine orientation, and how much of the tower and nacelle is illuminated by the radar, the expected radar cross-section (RCS) could be in the region of +50 $dBm^2$ to +60 $dBm^2$. This return is largely static, although it may vary slowly in time with wind-loading and as the turbine changes its yaw-angle with wind-direction. The large size of this static clutter reflection may be difficult for moving-target indication (MTI) or moving-target detection (MTD) processors in some radars to cancel. In radars having only modest receiver dynamic range, the receiver may be driven into limiting by the magnitude of the turbine returns. This may result in problems with pulse compression and MTI or MTD processing.

2. Large, discrete radar reflections from the moving rotor blades. The motion of the blades will impose a Doppler frequency shift on the radar returns. The observed spectrum of Doppler shifts is dependent on the rotation rate, the blade length and the yaw angle of the rotor with respect to the radar. With the axis of rotation of the rotor aligned along the look-direction of the radar, only a small Doppler modulation is expected as the blades will only have a small amount of relative motion. With the axis of rotation perpendicular to the radar LOS, the extent of the Doppler frequency spectrum is expected to range between ± 100 m/s over a full rotation. Since the rotor blades have large, curved surfaces, they are expected to exhibit a complex, orientation-dependent scattering behaviour that is a function of the yaw angle and the blade pitch setting. The maximum RCS of the blades may be of order + 45 $dBm^2$, exhibited as short duration "flashes", with smaller, time-dependent RCS scattering components being present between flashes. Scattering from the rotor may give rise to returns at the radar that may have significant RCS at Doppler frequency components up to ± 100 m/s. Such scattering components are likely to be above detection threshold and may pass through MTI/MTD Doppler filters intended to suppress zero- and low-speed clutter returns.

3. Large discrete clutter returns may affect cell-averaging constant false alarm rate (CFAR) detection threshold settings when processing range cells that include a turbine. The large return from the turbine may result in desensitisation of the radar in several range-cells either side of the turbine (see Figure 5). Note that at longer ranges, the larger cell size in azimuth tends to result in a greater probability of a turbine intersecting with a given range-azimuth cell.

4. Clutter maps designed to maintain detection of tangentially-crossing-targets may be affected. Coarse ground clutter maps may result in problems resolving crossing air targets between turbines. If the clutter map range-azimuth cell size is large enough to include several

turbines, the clutter map may suppress detection of low altitude crossing air targets that are flying above but between turbine towers.

5. Depending on the data processing algorithms used, the radar may experience a higher false alarm rate in the vicinity of a wind farm. The increased false alarm rate may result in additional loading of the plot extractor and track processor. The tracker may have to suppress the initiation of tracks on turbine returns and cope with the potential "seduction" of established tracks by false returns from wind turbines.

6. Some shadowing of radar coverage by turbine towers is expected locally behind towers at low elevation angles due to blockage of the radar beam.

Some example measured data for a single onshore wind turbine (see Figure 1) are shown below (Figure 2 - Figure 4). These data were produced by QinetiQ in a study now in the public domain [1]. It should be noted that the predicted and measured RCS values exhibited by offshore wind turbines may differ from those shown in these example Figures due to the larger turbine designs being considered for offshore use. It should be noted that the likely size of RCS returns after Doppler filtering are likely to contain scattered signals at a level much higher than might be expected from a small aircraft (≈ 0 $dBm^2$) in motion at low altitude immediately above a wind turbine.

Figure 1: An onshore wind turbine measured by QinetiQ using a 3 GHz instrumentation radar. The rotor diameter is 66 m in size. From [1].

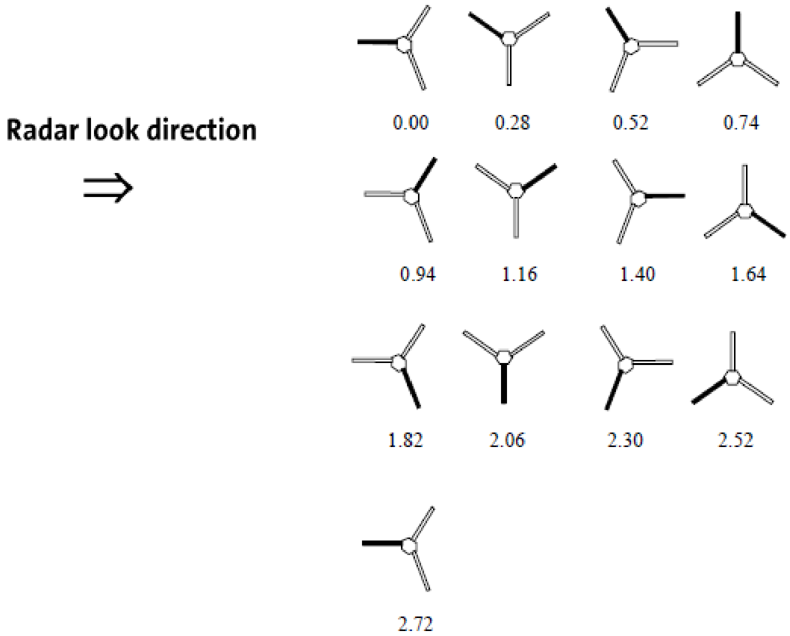


Figure 2: Estimated rotor blade position during radar measurements. The numbers indicate time in seconds. The radar is looking from the left of the page edge-on to the plane of the rotor. The rotor is turning clockwise as viewed into the page. From [1].

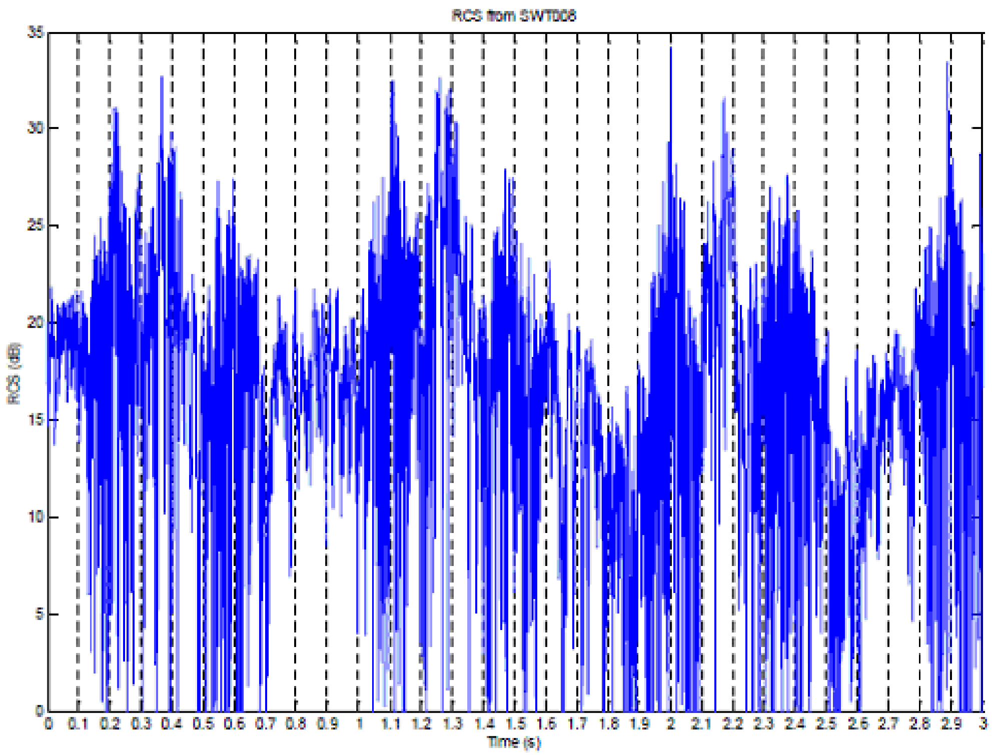


Figure 3: Measured RCS (relative to 1 $m^2$) of the wind turbine shown in Figure 1, viewed with the rotor oriented approximately edge-on. Estimated rotor positions and timings are as shown in Figure 2. From [1].

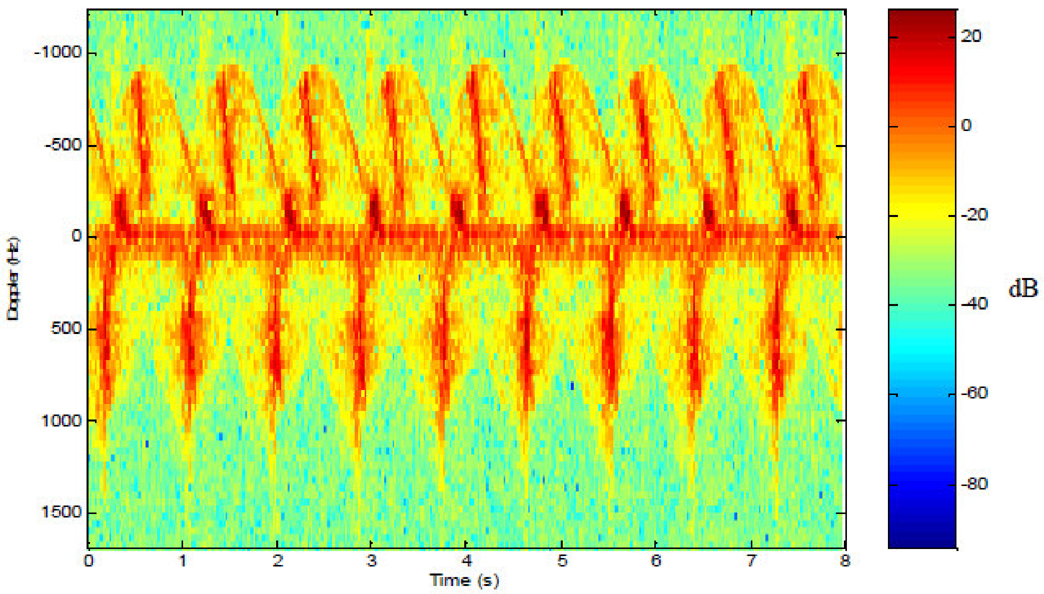


Figure 4: Doppler spectrogram of measured RCS (relative to 1 $m^2$) of wind turbine rotor viewed edge-on for just over three complete rotations of the rotor. This corresponds to the measurement geometry and timings shown in Figure 2 and time domain data part of which is shown in Figure 3.

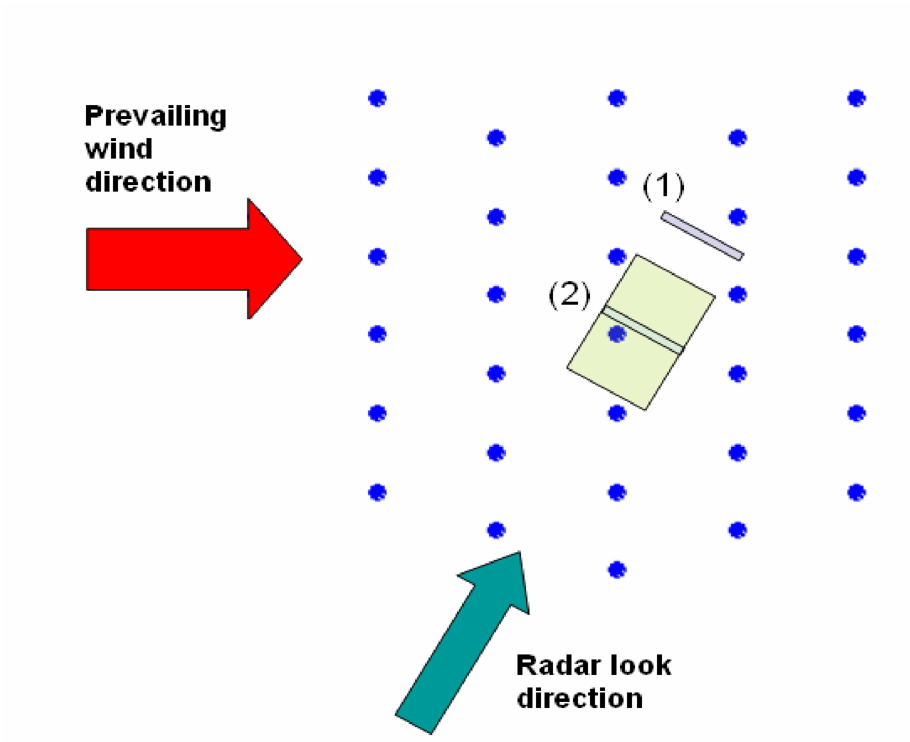


Figure 5: Schematic showing example range-azimuth cells for a pulsed radar above a wind farm (blue dots represent generic wind turbine locations in an idealised wind farm development). The possible minimum extent of a radar range-azimuth cell size is indicated by the small rectangle (1). If cell-averaging CFAR is used, with cells being averaged either side of a central test-cell (large rectangle (2)), there is a possibility that one or more turbines may be present in the reference cells used to set the CFAR threshold. Therefore the CFAR process has, potentially, to take account of large turbine clutter returns being present within its background averaging areas.

## 6 QinetiQ discussion

It is evident that a candidate in-fill radar system has to meet potentially difficult engineering requirements.

It is noted that some or all of the following features in a candidate in-fill radar may assist in meeting the requirements:

- Receiver instantaneous dynamic range > 70 dB.
- Low elevation and azimuth antenna sidelobes, particularly in upper elevation beams to suppress turbine returns appearing in these beams.
- Low range side-lobes after pulse compression to minimise leakage of large discrete clutter returns into neighbouring range bins.
- Clutter sub-visibility after MTI/MTD processing: > 55 dB, preferably > 60 dB.
- CFAR processor able to cope with clutter discretes of at least + 55 dBm$^2$ and maintain threshold against a 1 m$^2$ target in range-azimuth cells used to carry out cell-averaging ("background averaging").
- High range and azimuth resolution to reduce likelihood of target and turbine falling in same range-azimuth cell. A high radar operating centre-frequency may assist in achieving this.
- Small ground clutter map cell size, preferably << the inter-turbine separation distance.
- Good resolution in Doppler frequency, to assist in discrimination between air target returns and turbine blade returns. A pulse-Doppler radar able to produce fine Doppler resolution and capable of target velocity measurement may be at an advantage.
- High update rate on target, so as to assist tracker in maintaining plot association.

## 7 References

[A1] POUPART, G. "WIND FARMS IMPACT ON RADAR AVIATION INTERESTS - FINAL REPORT", DTI PUB URN 03/1294, September 2003. Available from UK DBERR website at: http://www.berr.gov.uk/energy/sources/renewables/publications/page18050.html

[A2] http://www.bwea.com/aviation/