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STEALTH TECHNOLOGY FOR WIND TURBINES

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STEALTH TECHNOLOGY FOR WIND TURBINES

FINAL REPORT

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EXECUTIVE SUMMARY

A significant proportion of new and existing wind farm planning applications submitted to regional agencies for consideration have been rejected due to objections raised on the basis of the potential for radar interference. The Stealth Technologies for Wind Turbines (STWT) programme was established to develop a reduced radar cross section (RCS) wind turbine system which addresses the planning objections by using a combination of materials and shaping techniques to reduce the overall RCS of a wind turbine, including the blades, nacelle and tower.

The combined use of passive materials and shaping to minimise the RCS of military platforms is well established. This project seeks to address this priority issue by using a combination of conventional and novel stealth technologies to reduce the overall radar cross section (RCS) of the wind turbine blades, nacelle and tower. The main objectives of the programme were to;

(i) identify the major RCS contributions from a turbine and understand which (in terms of overall RCS reduction versus cost) would most benefit from treatments / shaping

(ii) develop appropriate RCS treatments for the tower, nacelle and blades through a combination of turbine modelling, shaping and absorbing or reflecting materials design

(iii) demonstrate practical implementation of commercially viable RCS reduction techniques by the manufacture and characterisation of representative blade, tower and nacelle sections in order to de-risk the manufacture of a total turbine solution.

The programme was led by BAE Systems Advanced Technology Centre with Vestas Technology UK Ltd, the University of Sheffield and the University of Manchester as consortium partners.

Initial activities within the programme focussed on capturing the main requirements for a stealthy wind turbine where consideration was given to the large number of wind farm planning application objections raised at the time. Details of the radar systems were obtained in order to determine the radar operating frequencies of interest and a brief cost target exercise was undertaken to establish what additional costs may be acceptable. An RCS and radar modelling exercise was also undertaken to determine the levels of radar cross section likely to be required for each turbine component in order to mitigate the interference effects.

Initial modelling identified that the monostatic RCS of the tower and nacelle components could be reduced significantly by shaping alone without the need

for the application of radar absorbing materials (RAM). RAM treatments were developed for both components during the programme but the shaping technique was identified as preferable as it did not require any significant changes to the current manufacturing processes. In addition, the RCS of the nosecone was not significant.

Modelling work undertaken for both offshore and onshore wind farm scenarios indicated that with a shaped tower and nacelle, the main contribution in the RCS of a wind turbine was from the blades. An initial radar impact study identified that the shaping of the nacelle and tower components did reduce some of the interference effects caused by the wind farm but these were not completely removed as a result of the large contribution from the blades which provide the largest contribution to the RCS in a shaped turbine. RAM treatments were developed for integration into the current Vestas V82 blade components based on preserving the external geometry and manufacturing processes and on minimising the increase in mass and thickness within the blade.

A stealthy blade demonstrator section was manufactured based on a number of RAM schemes developed for application in a number of different regions within a blade component. The radar cross section of the blade demonstrator section was characterised in an anechoic chamber and compared to that of a standard (untreated) blade section of similar dimensions. Significant levels of RCS reduction were achieved although at a number of frequencies the performance was compromised by a number of difficulties including an operator error during manufacture.

RAM schemes were also developed for the tower and nacelle components and their performance validated through the manufacture and characterisation of a number of flat test panels.

A second stage of radar system modelling was undertaken to determine the impact of the shaping and RAM treatments on the interference of several wind turbines with local radar systems for both the onshore and offshore cases. A significant reduction in radar impact was predicted in each case.

Unfortunately, during the final stages of the programme Vestas had to significantly reduce their contributions to the programme due to high workloads in other areas within their business requiring that resources be reallocated to other projects. A significant amount of development activities were therefore not completed including manufacturing process development and the mechanical assessment of the proposed blade RAM schemes.

The STWT programme has addressed the major problem of the interference caused by wind farms on radar systems at the source to deliver a set of prototype turbine demonstrator components which make some progress towards de-risking the manufacture of a stealth wind turbine solution sufficiently to enable the manufacture of a full size, low RCS turbine for evaluation on a trial site.

The programme has delivered a comprehensive understanding of the major scattering sources and mechanisms on wind turbines and has identified both material and design methods which can be used to minimise the impact of wind turbines on target radars. In addition, radar system modelling indicates that the application of both shaping and materials solutions together have the potential to reduce the interference effects sufficiently to restore the ability of a radar to detect aerial or marine targets in the vicinity of a wind farm.

Solutions have been proposed for the nacelle and tower components that can be implemented without any significant changes to the current manufacturing process. A number of RAM treatments have been developed for the turbine blade components but further development work is required to fully understand the technical and commercial viability of applying the treatment to Vestas' blades.

A number of activities have been recommended in order to enable a fully treated turbine system to be installed and evaluated. Initial activities should focus on assessing the market potential for stealth wind turbine systems both within the UK and abroad and the requirements captured within the STWT programme should be reviewed and updated if necessary. Particular focus should be aimed at the radar operators and the wind turbine manufacturers.

The issues identified with the resistive material developed during the STWT programme should be addressed and further work undertaken in order to optimise the blade RAM schemes in terms of their performance and integration of the materials into the current blade components. Consideration should be given to a number of requirements not considered during the STWT programme including both the structural and lighting strike performance of the blades. When complete, the manufacture and installation of a stealthy turbine system will enable the effectiveness of the RCS reduction techniques to be quantified and the radar system models to be validated.

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2 Introduction

A significant proportion of new and existing wind farm planning applications submitted to regional agencies in the UK for consideration have been rejected due to objections raised on the basis of the potential for radar interference. Figure 2.1 shows the typical plan position indicator output from a small marine craft close to a wind farm. It illustrates the potential confusion caused by multiple reflections and azimuth sidelobe ‘smearing’ which can lead to “ghost” targets.

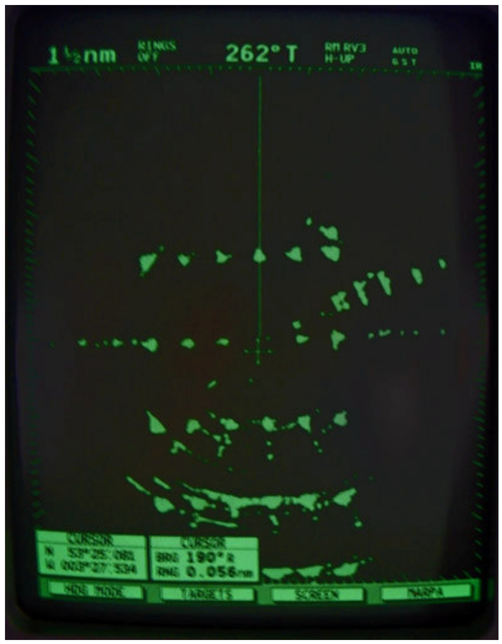

Figure 2.1: Small Ship Radar Showing Multiple Reflections within the North Hoyle offshore wind farm causing spurious targets to be displayed.

To address this issue, it is estimated that the total radar cross section (RCS) of a wind turbine system needs reducing by at least 25dBsm [1]. This can either be achieved by shaping the individual wind turbine components, the application of radar absorbing materials (RAM) or a combination of both.

This report is the final document generated as part of the Stealth Technology for Wind Turbines (STWT) programme as set out in the DTI Grant Offer Letter [2] and as defined in the programme Work Breakdown Structure [3]. The programme was established to develop a reduced radar cross section (RCS) wind turbine system which addresses those planning objections associated with radar interference by using a combination of materials and shaping techniques to reduce the overall RCS of a wind turbine, including the blades, nacelle and tower.

Each of the STWT programme partners brought a core set of skills to the consortium that was essential to delivering the objectives. The programme has been led by BAE Systems Advanced Technology Centre who understand (and have experience of) how to model the RCS of wind turbines, the effect of scatterers on radar systems and the design, manufacture and application of cost effective microwave absorbing materials to a wide range of land, sea and air platforms. Vestas Technology UK Ltd is a world leader in developing wind turbines; designing, manufacturing and installing blades, towers and nacelles. The University of Sheffield has over twenty years experience in the development of stealth technologies and is a leader in the development of active stealth for Doppler control. The University of Manchester has first hand knowledge of the UK radar types and user community, together with experience of developing techniques for lightning protection.

The main objectives of the programme were to;

(i) identify the major RCS contributions from a turbine and understand which (in terms of overall RCS reduction versus cost) would most benefit from treatments / shaping

(ii) develop appropriate RCS treatments for the tower, nacelle and blades through a combination of turbine modelling, shaping, absorbing or reflecting materials design

(iii) demonstrate practical implementation of commercially viable RCS reduction techniques by the manufacture and characterisation of representative blade, tower and nacelle sections in order to de-risk the manufacture of a total turbine solution).

3 Requirements Capture & Treated Turbine Component Cost Targets

Information was collected during Work Packages 1 and 2 activities [4] in order generate a set of requirements to assist the design of a reduced radar signature wind farm. General information which might have an impact on the application of aerospace stealth technology to wind farms was also collected such as typical manufacturing methods for various components, reasons behind particular wind turbine layouts in a farm, and unclassified performance data on a range of radars operated by parties who have raised objections were also collected. This information is presented in the report where commercial and security issues permit.

3.1 Radar Frequency Requirements

The principal organisations and related tasks on which current and future objections might be raised were divided into two main groups; aviation and marine stakeholders.

The MoD's Defence Estates (DE) organisation has responsibility for safeguarding the interests of defence establishments, particularly in this instance the provision of surveillance for air defence purposes and military air traffic control. The UK National Air Traffic Services (NATS) has responsibility for providing air traffic control to civil and to some extent military users of the service, both for airport terminal approach and 'en-route' air vehicles. Other stakeholders such as test and measurement ranges and the meteorological office, using radars to obtain data for forecasting, were also identified.

Marine stakeholders included the Maritime and Coastguard Agency (MCA), operating Vessel Traffic Services, Port Authorities and the operators of marine craft. The performance characteristics of the various radar types operated by the stakeholders and the anticipated or observed impacts on performance are provided in [4].

The principal operating frequencies for the various victim radars were identified. From the information captured, it is clear that the frequency range 2.7-3.1GHz would potentially assist in the recovery of the performance of radars operated by a number of important stakeholders. The majority of current (and probably future) air defence (AD) radars, though frequency agile, operate within this band (2.7-3.1GHz), as do civil air traffic control (ATC) (2.7-2.9GHz) and military ATC (2.7-3.05GHz). This band also encompasses radars operated by many of the marine stakeholders. The vessel traffic system (VTS) operates in the 3.05-3.1GHz band as do major vessel marine radars. Performance in this band therefore, would potentially afford significant impacts on the performance of radar for both aerial and marine stakeholders. Given that a large proportion of future wind farms may be constructed offshore, the inclusion of significant losses at frequencies over which marine vessel radars and some VTS equipment operate may significantly improve the marketability of any solution. Consequently, the inclusion of reflection losses in the range 9.1-9.41GHz is also considered highly desirable.

3.2 Target Cost Limits

The target cost of the potential solutions is considerably lower than the figures cited for the current developmental solution in [4]. The cost of the nacelle and tower solutions was found to be insignificant in comparison to a set of three blades where a total surface area of ~170m^2 per blade is likely to require treatment. Initial cost estimates indicated that it was likely to be possible to supply a cost viable blade solution for production quantities of the RAM components.

3.3 RCS Reduction Requirements

The level of RCS reduction required to yield significant detectability improvements to a 'victim' radar system is difficult to estimate to any degree of accuracy without detailed modelling. This requires information on the radar performance characteristics and signal processing methods with, propagation and so terrain characteristics between the farm and radar. The RCS of the wind farm scatterers and that of the target are also required. These calculations were performed later on in the programme [1], but no detailed work had been done at the time the requirements were being captured.

It is clear that in the case of AD and ATC radars, a reduced RCS wind farm has the potential to give rise to some improvement in detectability by reducing the returns to a radar resultant from sidelobe illumination of a wind farm. This may be achieved in part by various improvements to monostatic radars [5], and by signature reduction of wind turbines in the farm. For example, in the case of a typical AD radar with sidelobes 30dB down on the main beam, a wind farm of perhaps 50dBsm, subject to sidelobe illumination will afford a level of received signal around 10dB down on a 0dBsm target illuminated by the main beam. Further signature reductions of the farm, will therefore result in increasing improvements to the effective signal to noise. Previous work has indicated that the use of reduced RCS wind turbines will prove most effective when used as part of a holistic solution to the problem. The sidelobe illumination problem makes the development of this technology equally applicable to marine stakeholders. Generally, the sidelobes associated with marine radar apertures are significantly higher than for AD/ATC radars and at least one report has described evidence of sidelobe illumination effects resulting in the appearance of 'ghost' images of wind farms. The low cost and large number of marine vessel radars makes the modification of such sensors impractical in the short term for most cases.

3.4 Other Requirements

Additional work carried out in Work Package 4 [6] gave further consideration to the top level requirements for the signature reduction of the Vestas V82 wind turbine and identified specific requirements for the tower, blades, nacelle and nosecone. The requirements are sub-divided into mechanical, environmental, electrical and other requirements. Relevant standards against which existing components are already qualified are referenced where compliancy will be required for the reduced RCS solutions.

A summary of the key performance requirements for a low RCS wind turbine system is presented in Table 3.1.

Property	Requirement
Electromagnetic	
Operating Frequency Range	2.7 to 3.1GHz and 9.1 to 9.41GHz
Radar Cross Section Reduction	20dBsm in total
Lightning Strike Protection	Compliant with IEC 62305 1-5 2004
Physical/Mechanical	
Mass Increase	Minimised
Manufacturing	Maintain existing methods/processes
Environmental	
Temperature Operating Range	-40°C to +60°C
Exposure Resistance	UV
Other	
Cost	<10% increase in manufacturing cost
Service Life	>20 years
Security Classification	Unclassified

Table 3.1 : Key Requirements for Reduced RCS Wind Turbine System

Table 3.2 details the additional requirements identified during Work Package 5 [7].

Solution Parameter	Tower	Blade	Nacelle
Mass/area	<10kg/m^2	<5.4kg/m^2 (blade mass increase of 507kg)	<1kg/m^2
Thickness	Not constrained	3 additional 0.9mm plies, max.	<13mm, monolithic
Solution Cost	£10,000	£100,000	£10,000
Reflection Loss	-20dB	-10dB	-15dB
Frequency (band centre)	2.9 and 9.25GHz	2.9 and 9.25GHz	2.9 and 9.25GHz
Preferred Solution	Shaping then Parasitic RAM	Structural RAM	Shaping the Structural RAM

Table 3.2 : Additional Requirements for Reduced RCS Wind Turbine System

4 RCS and Initial Radar Modelling

A number of initial modelling activities were undertaken in Work Package 3 [1] in order to understand the effect of wind farms on radar and to support the stealth programme. The first activity studied the RCS phenomenology of a wind turbine, including predicting the Doppler signature. The second activity was to develop a radar processing model so the effect of the wind farm can be modelled from a radar perspective.

4.1 RCS Geometries

CAD data files were obtained from Vestas for each of the V82 turbine components. The data files were cleansed in order to make it suitable for the electromagnetic modelling activities. The geometries were then modified to enable each component to be mated together in order to allow modelling activities to be undertaken on the full turbine system. In addition, the blade was split into several sections in order to enable an approximation of the Doppler spectrum to be generated. This enabled the scattering to be calculated from individual regions rather than treating the target as a point scatterer. Figure 4.1 shows a screenshot of the composite CAD model.

Figure 4.1: Composite CAD Model

4.2 RCS Modelling

The above CAD geometry files were used to develop an RCS model of a wind-turbine. All modelling activities reported used the co-ordinate system defined in Figure 4.2.

- Yaw (Y), Rotation Angle (R), Turbine Pitch (T), Blade Pitch (B)

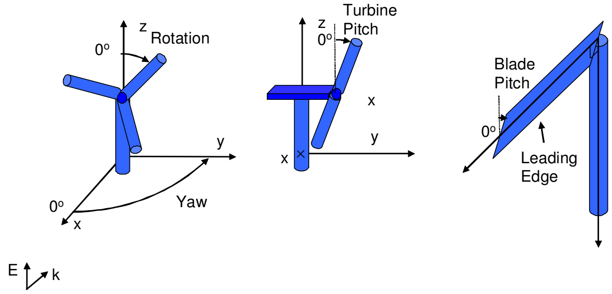

Figure 4.2: Definition of Co-ordinate System

An assessment of a number of available EM codes was undertaken in order to establish which codes were appropriate for each aspect of the simulation work based on the following;

- frequencies assumed to be 3GHz and 10GHz
- turbine external surface assumed to be a Perfect Electric Conductor (PEC)
- RAM treatments would be required at some stage
- blade length is ~1400λ and tower height is ~2500 at 10GHz, so the model is electrically large.
- geometry files contain moderately curved elements which must be captured.

The only modelling approach which was suitable using the available computing platforms was physical optics (PO). For sections of the problem (excluding the tower, for example, significantly reduces the problem size) and for lower frequencies, BAE Systems, Advanced Technology Centre Multilevel Fast Multipole code (FM3D) [8] provided a useful full-wave solver to validate the PO approximation. Two potential PO codes were available, a commercial code FEKO [9] and an in-house code Mitre [10]. The outputs of both codes were compared for a number of different turbine configurations. At frequencies where the PO approximations are valid the agreement between FM3D and PO was excellent. At higher frequencies the limitation of using flat facets resulted in the problem being electrically too large for FEKO to model so MITRE was used throughout the work. There were some differences between the outputs of the codes at low frequencies but, generally, broad agreement was obtained between the codes for the range of test parameters that were of interest. Further details of both the comparison and the modelling results can be found in [5].

The total monostatic RCS from the PEC turbine at 3GHz is presented in Figure 4.3 and Figure 4.4 for 0° and 90° yaw respectively.

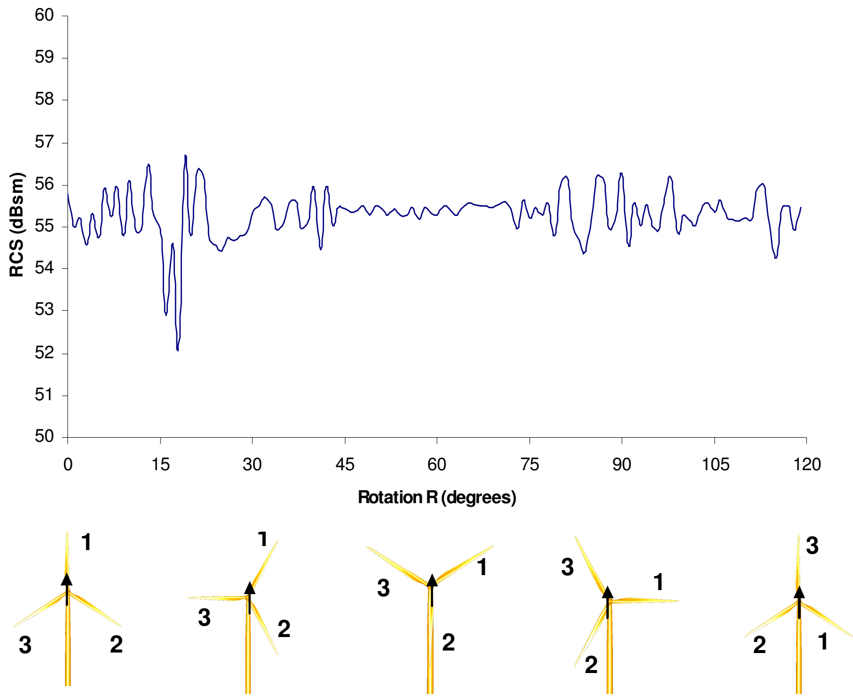

Figure 4.3: Total Turbine RCS at 0° Yaw (3GHz)

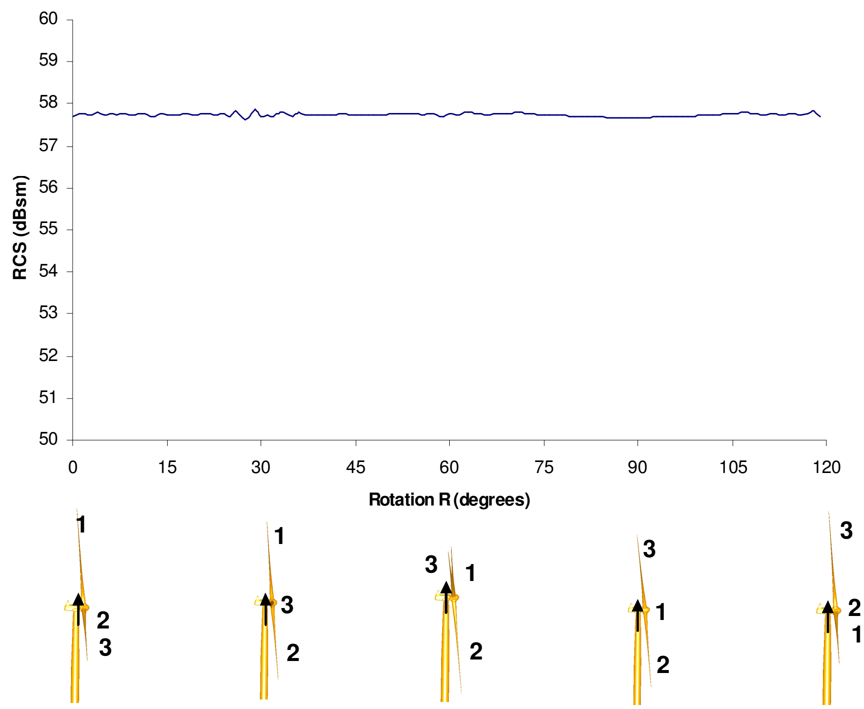

Figure 4.4: Total Turbine RCS at 90° Yaw (3GHz)

Similarly, the total RCS from the PEC turbine at 10GHz is presented in Figure 4.5 and Figure 4.6 for 0° and 90° yaw respectively.

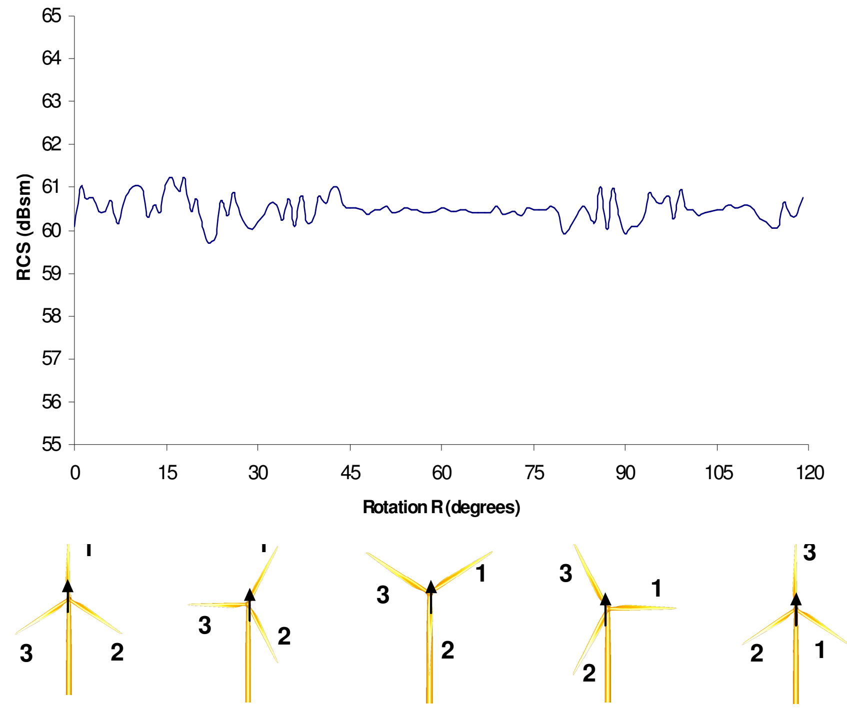

Figure 4.5: Total Turbine RCS at 0° Yaw (10GHz)

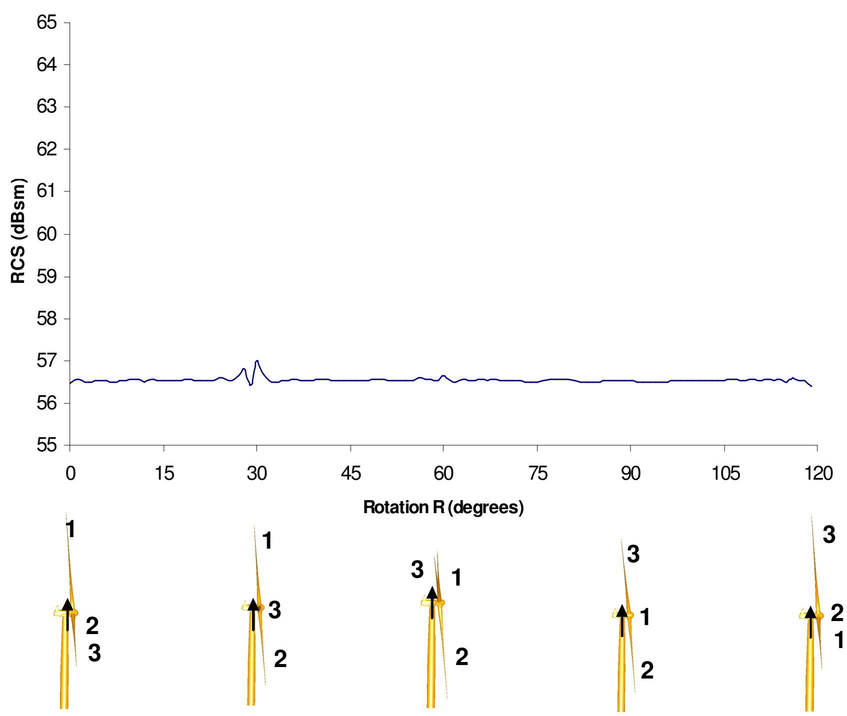

Figure 4.6: Total Turbine RCS at 90° Yaw (10GHz)

At 0° yaw the RCS fluctuates with blade angle by around 5dBsm whereas at 90° the RCS is constant. Further modelling at 3GHz indicated that at all angles the tower RCS dominates the total signature. At 0° yaw all sections of blade contribute to the RCS, peaking at around 40dBsm (20dB below the tower). The nacelle and hub do not significantly contribute to the total RCS. This is expected since the hub is the physically smallest component and is already shaped in such a manner that it would scatter radiation away from the monostatic direction. At this yaw angle the nacelle is obscured by the blades and hub, and even viewing as an individual component is also shaped and does not present a flat surface to the monostatic direction. The fluctuating response, therefore, in the total RCS is due to the static tower RCS and blade RCS.

At 45° yaw the nacelle was found to provide a large RCS contribution (10dB below the tower) due to the large flat surface presented by the side panels. On the trailing edge of the blade, only the section of blade towards the hub contributes significantly to the RCS, due to the thin aerodynamic shape of the surface. All sections along the length of the leading edge of the blade contribute to the total RCS (the leading edge being wider than the trailing edge so this result is not surprising). The peak RCS of the blade edges is lower than the blade face by around 20dB, so is around 40 dB below the tower. This results in a flat RCS profile of the total turbine at this yaw angle.

These results have implications on the design of stealth materials into the blade. The surface of the blades contributes most significantly, so must be treated first. The leading edges of the blades do not need to be treated as the most the faces will be reduced by will be around 20dB. Most of the trailing edge does not need to be treated as the widest part towards the hub dominates.

The tower is constructed from a cylindrical section and two truncated conical sections. By dividing the cone into a series of discrete cylinders (using the average radius for the conical sections) and forming an incoherent sum, the expected tower RCS is 56dB, which agrees with the MITRE predictions.

4.3 Radar System Modelling

The radar system modelling activities were shared with BAE SYSTEMS Advanced Technology Centre [1] considering the Crystal Rig II onshore wind farm and the University of Manchester [11] considering the London Array offshore wind farm. The modelling activities investigated the impact of wind farms on an air defence and marine radar system for the onshore and offshore cases respectively. A comparison/cross-validation of the radar system models is summarised in Annexe A.

4.3.1 BAE SYSTEMS Radar Model

A signal-level simulation model was developed and validated to simulate the impact of wind farms on radar detection performance. The model synthesises signals from a wind farm, the environment (clutter), targets and system noise. The clutter and noise were based on appropriate statistical models; the clutter model includes either sea or land clutter. The radar model consists of typical processing stages in military AD and civil ATC radars, including MTI, clutter map, FFT, CFAR and thresholding. The model includes a GUI for easy data input. The computation of backscatter signals from a wind farm include predicted RCS data, discussed separately in this document, and is a function of a number of radar parameters, including RF, antenna pattern and the radar/wind farm geometry.

A radar model test case was run to determine the effect of the Crystal Rig II wind farm in East Lothian on the Type 93 Air Defence (AD) radar based at Brizlee Wood. The modelling considered the following situations;

- Target behind the wind farm; Blades side-on
- Target within 1km of the wind farm; Blades side-on
- Target in the wind farm; Blades side-on
- Target behind the wind farm; Blades face-on
- Target within 1km of the wind farm; Blades face-on
- Target in the wind farm; Blades face-on

Further details of the radar and wind farm parameters used in the model can be found in [1].

The results of the modelling are summarised in Table 4.1. The table shows the level of reduction required to achieve detection of the specified target for two different wind farm cases: blades side on and face-on, respectively. The level of reduction also depends on the relative position of the target and wind farm.

Target Pos.	Aspect	Blade	Hub	Nacelle	Tower	Comments
Outside Wind farm	Side-on	5	-	5	20	**Target detection affected by Wind farm range sidelobe returns**
	Face-on	10	-	-	20	
Within 1km(*)	Side-on	25	-	25	40	**Target detection affected by elevated CFAR thresholds**
	Face-on	25	-	-	40	
In Wind farm	Side-on	30	5	30	40	**Target detection affected by elevated CFAR thresholds**
	Face-on	**30**	**5**	**-**	**40**	

Table 4.1: Summary of required RCS reduction in dB

(*) 1km is the width of the CFAR window used to form the background noise average

The impact study has produced a number of findings as follows;

Where the spatial separation between target and wind farm is small, or the target is "inside" the wind farm, and the wind farm has side-on aspect to the radar, this presents the worst case scenario. The towers require the largest level of RCS reduction, of the order of 40dB. Even so, the nacelle and blades also require up to 30dB of RCS reduction. In addition, the radar threshold needs to be increased to mask the wind farm.

Where the spatial separation between target and wind farm is large, these requirements are reduced by approximately 20dB. This level of reduction, together with elevated radar thresholds, renders the wind farm undetected.

In either case, if the requirement is to detect the target, irrespective of the detectability of the wind farm, this is achieved with smaller levels of RCS reduction.

From the table above the turbine hubs require very little RCS reduction, of the order of 5dB.

The nacelle, on the other hand, requires up to 30dB RCS reduction, with the worst case being at side-on aspect. Since the aspect cannot be pre-determined, this worst case reduction should be assumed necessary.

MTI processing has reduced the stationary components of each turbine by the expected amount. Blade signals are only partially reduced in the general case due to the spread of Doppler observed by the radar. However, in the special case of the blades being face-on to the radar, they are still a problem and require RCS reduction. This is because, although blades face-on present a narrow spectrum to the radar the RCS of the blades increases. This largely negates the attenuation achieved by MTI processing due to the limiting in MTI performance modelled.

The large spatial extent of a wind farm presents a range of yaw angles to the radar. This has the largest impact on nacelle returns since its RCS drops rapidly with yaw angle from 90°.

There is some small trade-off between RCS reduction of the various turbine components but this will depend on the number and disposition of each turbine in a farm and its aspect to an affected radar.

If the limit to MTI attenuation is actually better than that modelled (30dB) this will relax the required RCS reductions reported above.

4.3.2 University of Manchester Radar Model

A second radar system model was developed by the University of Manchester to again simulate the impact of wind farms on radar detection performance. As above, the radar model simulated signals from a wind farm, the environment (clutter), targets and system noise. In this case the radar model had the benefit of offering a Plan Position Indicator (PPI) plot as an output.

A radar model test case was run to determine the effect of the North Hoyle wind farm on a small marine navigation radar system with the average RCS of each wind turbine assumed to be 61.4dBsm based on far field calculations undertaken previously. The results of the model for this are presented in Figure 4.7 below in the form of a PPI plot. It can be noted that there are significant returns from sidelobes detections and ghost targets extending up to 2 km from the radar.

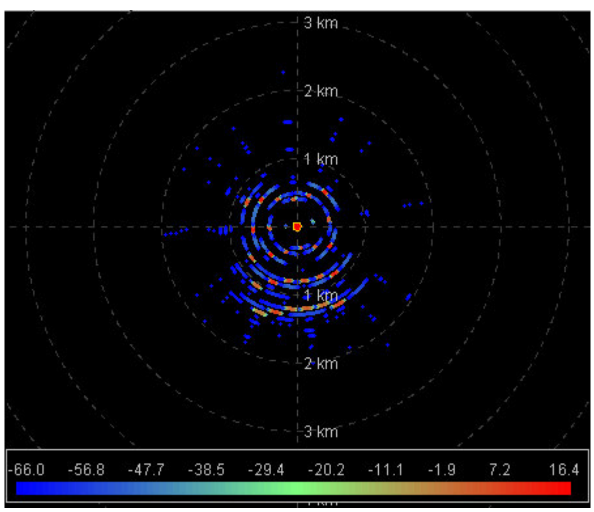

Figure 4.7: Simulated PPI Plot from Boat located in North Hoyle Wind Farm

The model was used to predict the returns from the turbines after reducing the RCS of each turbine by 5, 10 and 20 dBsm in order to provide an indication of levels of RCS reduction likely to be required in order to overcome the sidelobe detection and the appearance of ghost targets due to multiple reflections within the farm.

Figure 4.8 shows the effect of reducing the turbine RCS by 5 dBsm. In this case the false detections of multiple reflections still appeared but there was a significant reduction in the number of and the magnitude of the returns from ghost targets. The sidelobe returns still offer the potential to cause confusion and target tracking issues.

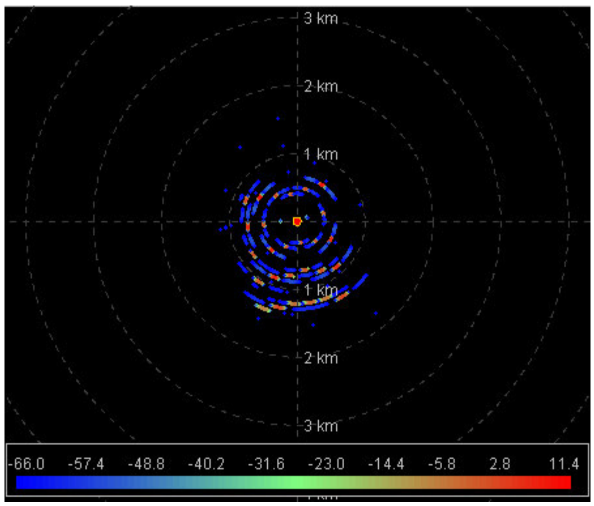

Figure 4.8: Simulated PPI Plot with RCS Reduction of 5dB per Turbine

Figure 4.9 presents the results for a turbine RCS reduction of 10 dBsm. In this case the ghost target detection has been eliminated and the sidelobe detection of nearby wind turbines has been reduced substantially although it is still visible on the PPI display.

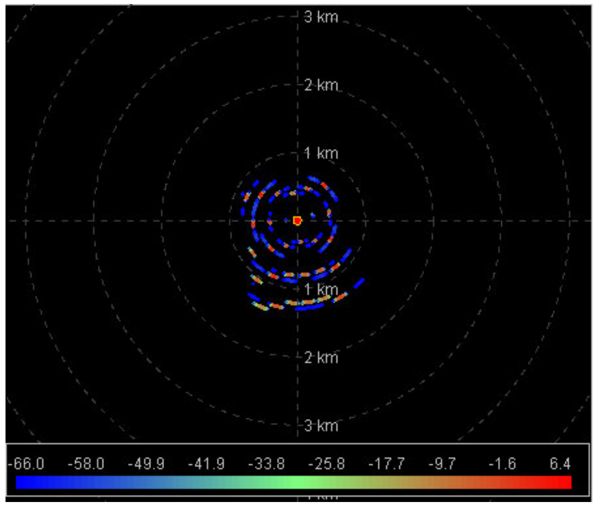

Figure 4.9: Simulated PPI Plot with RCS Reduction of 10dB per Turbine

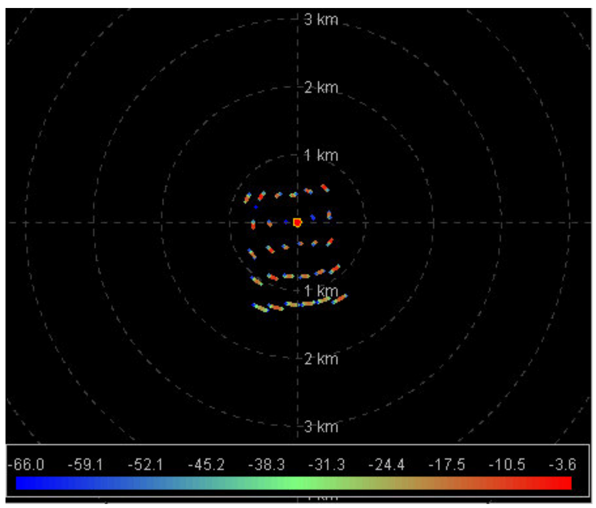

Figure 4.10: Simulated PPI Plot with RCS Reduction of 20dB per Turbine

Figure 4.10 presents the results for a turbine RCS reduction of 20 dBsm. In this case the detection through sidelobes and the appearance of ghost targets have been removed completely such that the PPI plot clearly shows the location of each individual turbine.

It should be noted that the turbine RCS values in the near field at ranges between 0 and 2 km are significantly lower than that of the far field. Modelling using the near field RCS approximation showed no sidelobe detection or ghost targets displayed on the PPI due to the lower turbine RCS properties which occur as a result of the radar being relatively close to the turbines. However, ghost targets and detection through sidelobes were clearly seen in measured data obtained from a small ship during a visit to the North Hoyle wind farm. It was therefore recommended that the far field RCS data be used in future radar system model runs as it represents the worst case turbine RCS properties.

5 Turbine RCS Reduction through Shaping

A number of modelling activities were undertaken in Work Package 10 to assess the potential reduction of Radar Cross Section (RCS) of the V82 wind turbine through shaping. It was not within the scope of this programme to consider modifying the shape of the blade component and so it was assumed that the blade target RCS reductions would be achieved through the application of RAM. The shaping studies therefore focussed on the tower and nacelle components only using relatively simple shaping techniques only.

5.1 Tower Shaping

The towers used for the Vestas V82 turbines are constructed from rolled steel sheets. The sheets are rolled into cylindrical or conical sections and seam welded. Several sections are then welded together and flanges placed at either end. These composite sections are fitted with peripherals such as ladders and access panels/doors. The sections are transported to the wind farm site and bolted together at the flanges. The aim of this work was to produce low RCS turbines without significant modifications to the design or manufacturing process. This limits the shaping options to changing the dimensions of the existing cylindrical and conical sections. Other cross-sections are not viable due to increased manufacturing cost. Due to transportation of the tower sections, the maximum diameter to transport by road is 4.15m. The diameter of the top of the tower is fixed by the choice of nacelle.

The first stage of the study focussed on establishing how much the existing V82 design needs to be modified to yield a suitable RCS reduction. The diameter of the base and top of the tower and the tower height were left constant but the relative heights of the conical and cylindrical sections were varied. The dimensions and variables are illustrated in Figure 2.1.

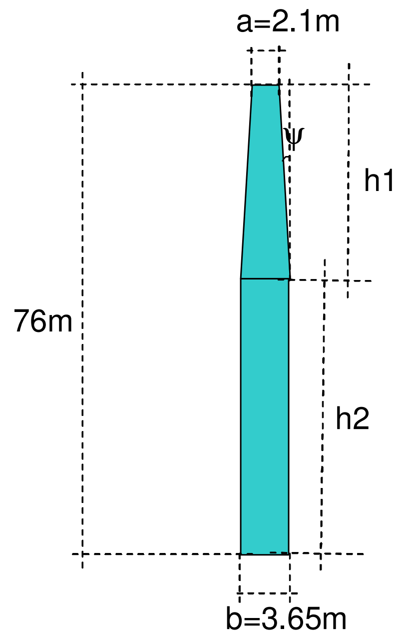

Figure 5.1: Dimensions and variables used for modification of V82 tower

The results for varying the slope angle are given in Figure 5.2 and Figure 5.3 for 3GHz and 10GHz respectively. The current V82 is clearly not optimal and significant RCS reduction can be achieved as the height of the conical section is increased up to the limiting case (an entirely conical tower) where the RCS reduces by approximately 40dB.

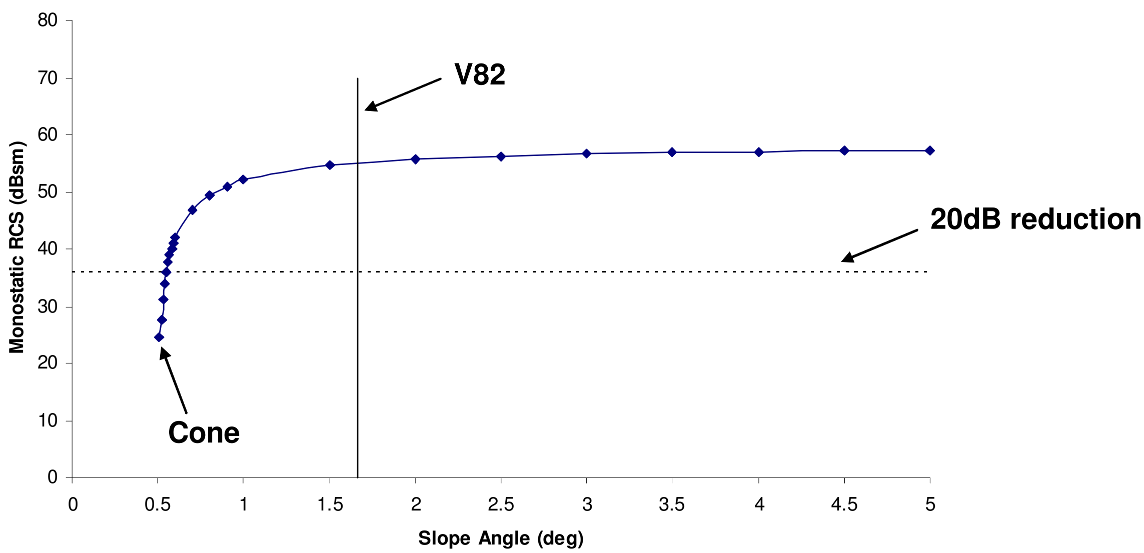

Figure 5.2: RCS variation with slope angle for V82 tower at 3GHz

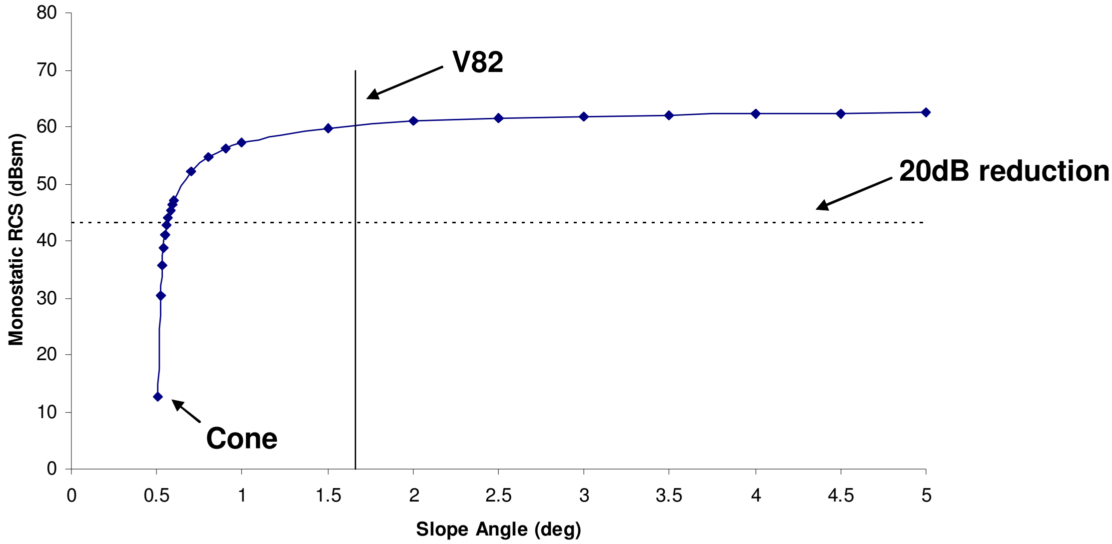

Figure 5.3: RCS variation with slope angle for V82 tower at 10GHz

The work identified that an entirely conical tower appeared to provide the optimum shape in terms of RCS reduction. The top diameter of the tower remained fixed to mate with the nacelle. The variation of RCS at 3GHz and 10GHz as the base diameter was varied as shown in Figure 5.4.

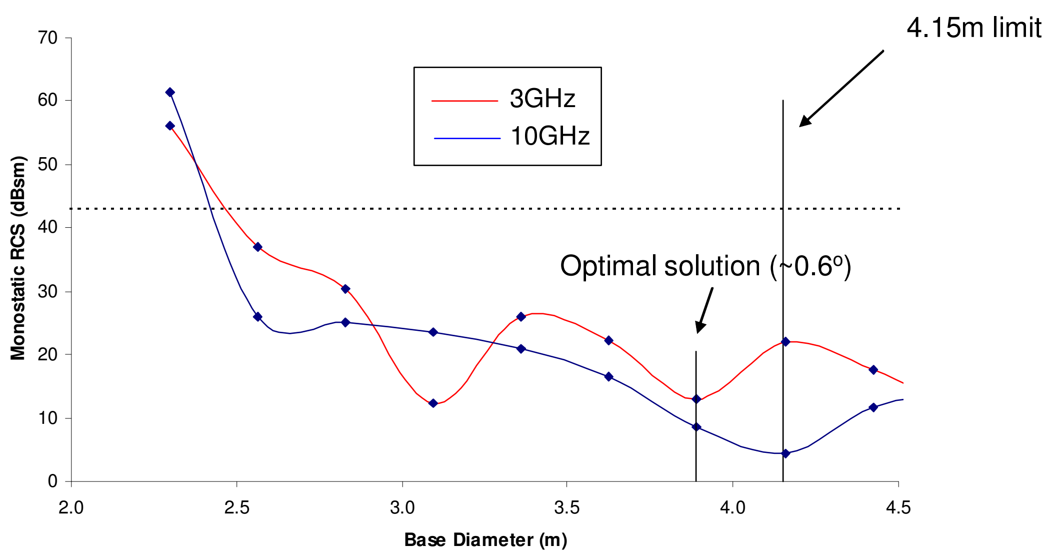

Figure 5.4: RCS of conical tower at 3GHz and 10GHz

Extending the base beyond the current V82 diameter, but within the transportation limits of 4.15m allows further reduction of RCS of the tower at both frequencies. The optimum tower base diameter, which minimises the RCS at both frequencies, is ~3.9m. This achieves an RCS reduction of approximately 40dB at 3GHz and 50dB at 10GHz.

To assess the effect of the tower RCS reduction on the total turbine RCS, the total RCS of the turbine with the shaped tower compared to the RCS of the V82 at 3GHz was calculated as shown in Figure 5.5 and Figure 5.6 for 0° and 90° yaw respectively. It can be seen that at some rotation angles the RCS has decreased by as much as 50dB, but at others the reduction is only as small as 10dB.

Further modelling indicated that with a shaped tower the blades became the dominant scatterers. However, for a yaw angle of 90° the nacelle was identified as dominant. The findings were the same for the 10GHz case.

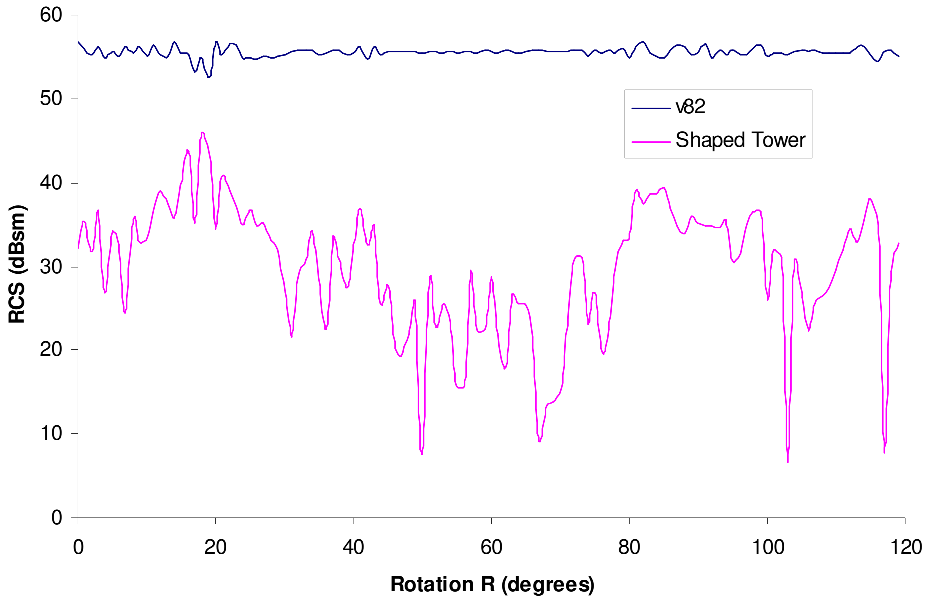

Figure 5.5: Total RCS of turbine with shaped tower at 3GHz and 0° yaw

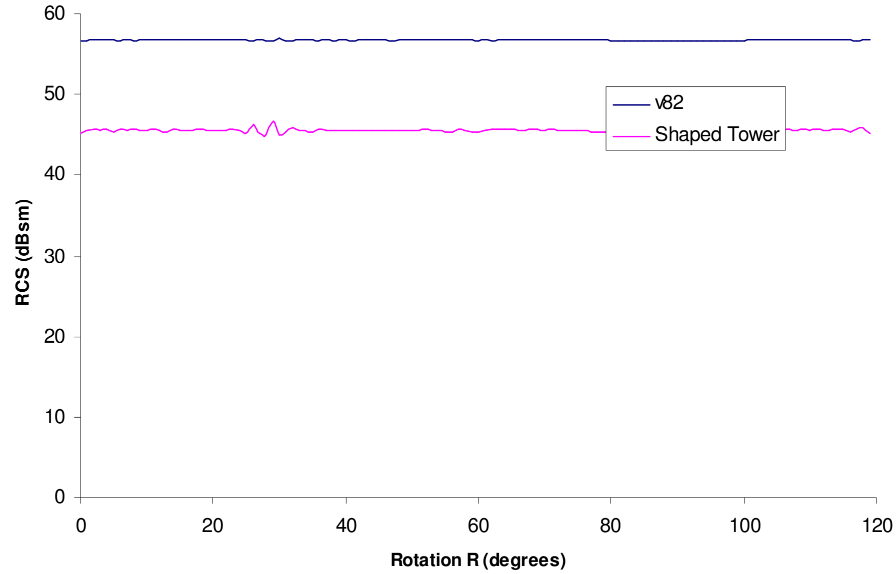

Figure 5.6: Total RCS of turbine with shaped tower at 3GHz and 90º yaw

5.2 Nacelle Shaping

The nacelle is a candidate for shaping as it is simply a cover for the turbine components and has little structural or aerodynamic requirements. The work focussed on keeping redesign to a minimum in an attempt to minimise design and manufacturing cost increases. Previous work had identified that it was only the side on (yaw = 90°) where the nacelle contributed significantly to the total turbine RCS. A side-on CAD view is shown in Figure 5.7. The nacelle is divided up to three sections to assess the RCS from each section and direct the shaping.

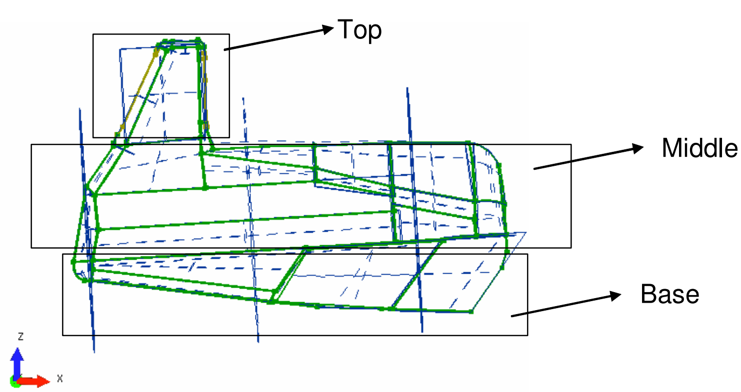

Figure 5.7: Nacelle CAD Model

Initial modelling indicated that the whole of the side of the nacelle required shaping in order to achieve the required RCS reductions. In all cases the RCS was found to peak in the side-on direction indicating that the nacelle would only need to be shaped away from the 90° and 270° yaw directions.

The simplest method of shaping to reduce the side-on RCS of the nacelle was found to be to slope the sides. To determine the slope angle to shape the nacelle, the RCS for a 10 degree cut in elevation was predicted, as shown in Figure 5.8. Figure 5.9 shows an example of the results for the middle section of the nacelle at 3GHz.

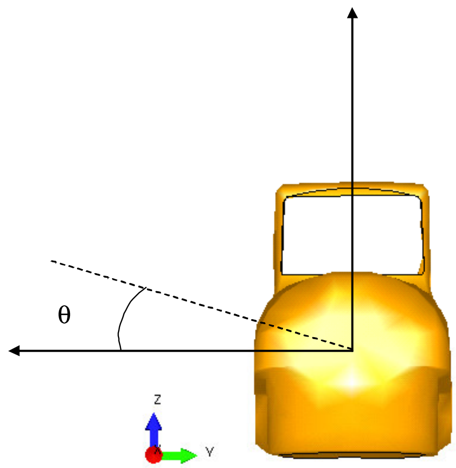

Figure 5.8: Elevation cut to assess optimum slope angle

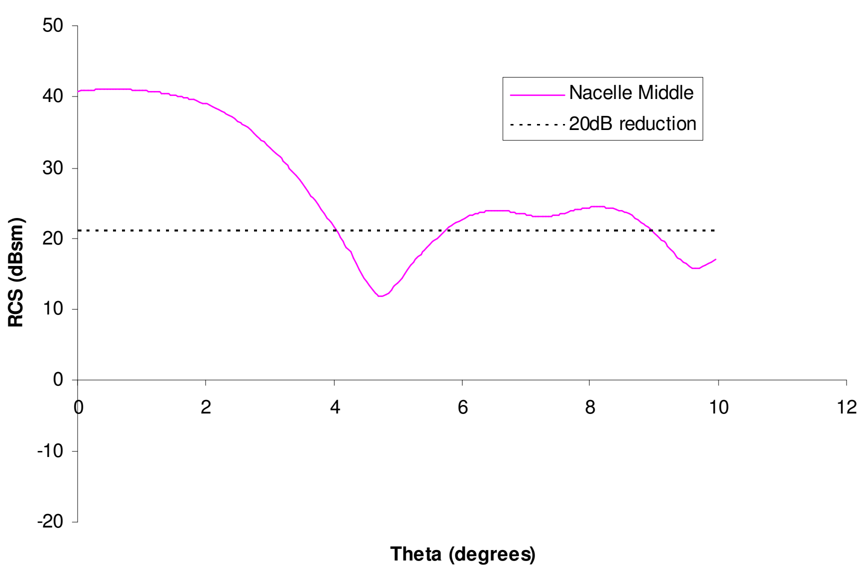

Figure 5.9: Elevation cut of nacelle middle section at 3GHz

In general, angling the sides by around 8° yielded an RCS reduction of at least 20dB. The CAD for the nacelle was therefore modified by this angle. However, rather than slope all surfaces in the same direction and create a stepped nacelle, the surfaces are extruded along joining edges in order to simplify the CAD modifications and minimise the geometry changes.

5.3 Fully Shaped Turbine

RCS predictions were undertaken for the new wind turbine design with shaped tower and nacelle prior to the application of any RAM treatments within the blade. The CAD model of the shaped turbine is shown in Figure 5.10.

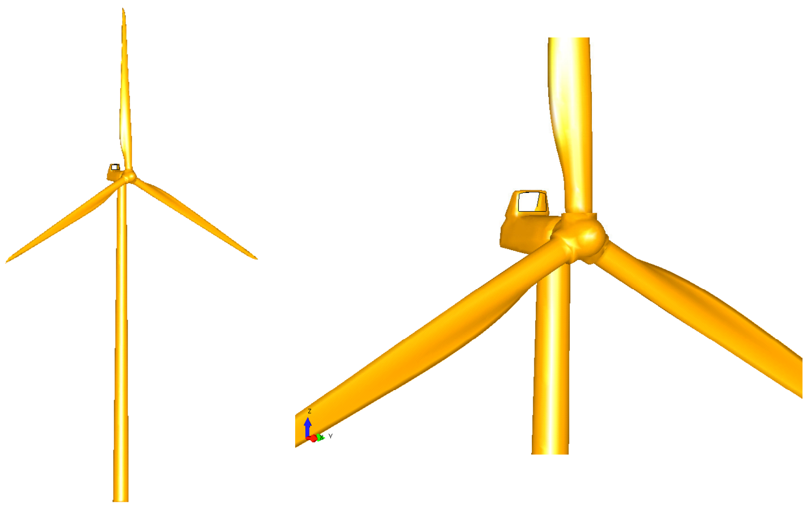

Figure 5.10: CAD model of shaped wind turbine

The total RCS of the turbine for 0° and 90° yaw at 3GHz is given in Figure 5.11 and Figure 5.12 respectively. Results for 10GHz are given in Figure 5.13 and Figure 5.14. For both frequencies the application of shaping to the tower and nacelle components has reduced the total RCS of a complete turbine in line with the requirements. However, the integration of RAM within the blade component is still key if the overall target RCS reductions are to be achieved.

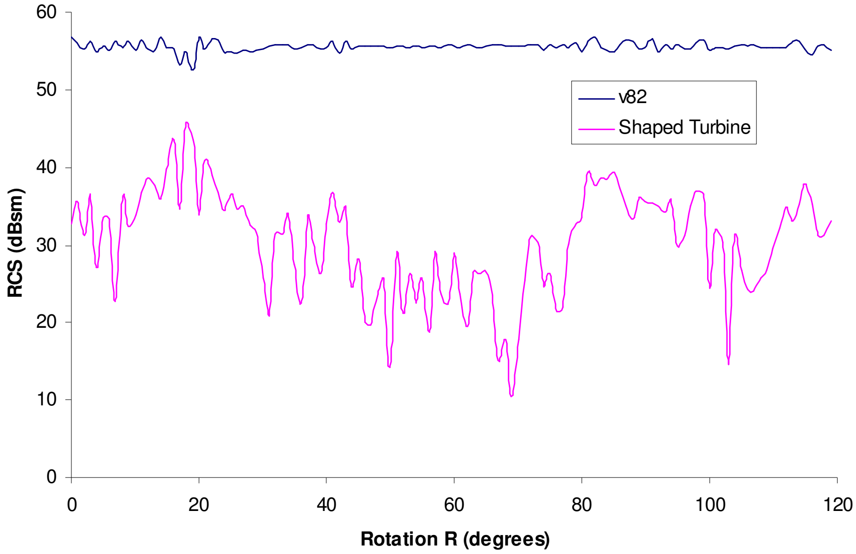

Figure 5.11: Total RCS of shaped turbine at 0° yaw at 3GHz

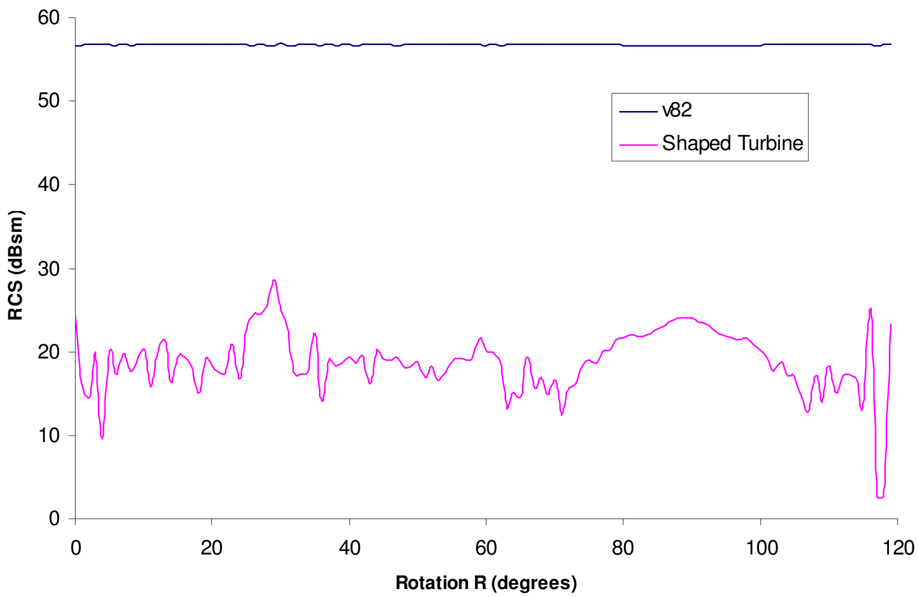

Figure 5.12: Total RCS of shaped turbine at 90° yaw at 3GHz

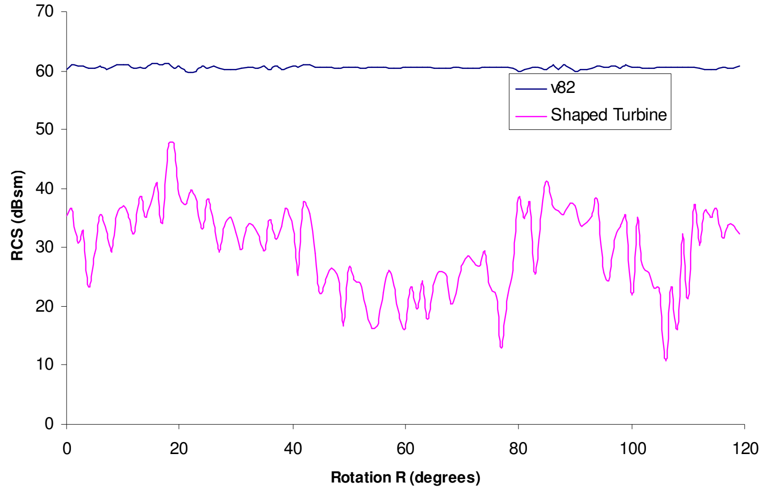

Figure 5.13: Total RCS of shaped turbine at 0° yaw at 10GHz

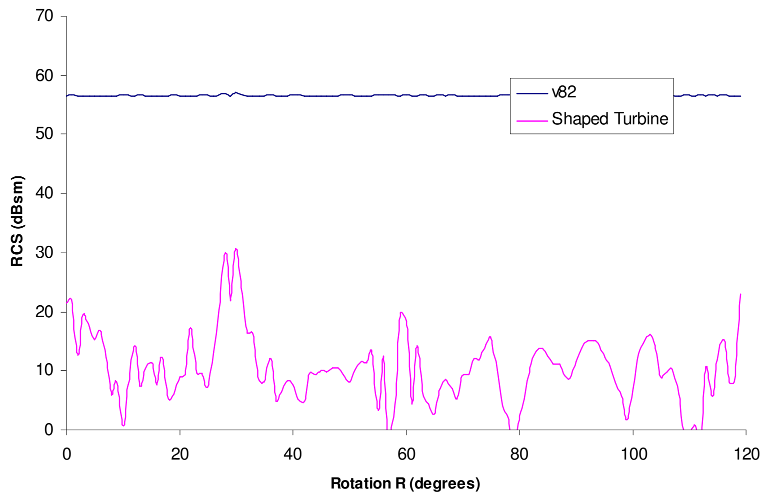

Figure 5.14: Total RCS of shaped turbine at 90° yaw at 10GHz

6 Candidate Solutions

6.1 Passive Solutions

During Work Package 5 [7] the top level design parameters were translated into design goals for each of the individual turbine components based on their contribution to the overall RCS of the turbine as illustrated in Figure 6.1.

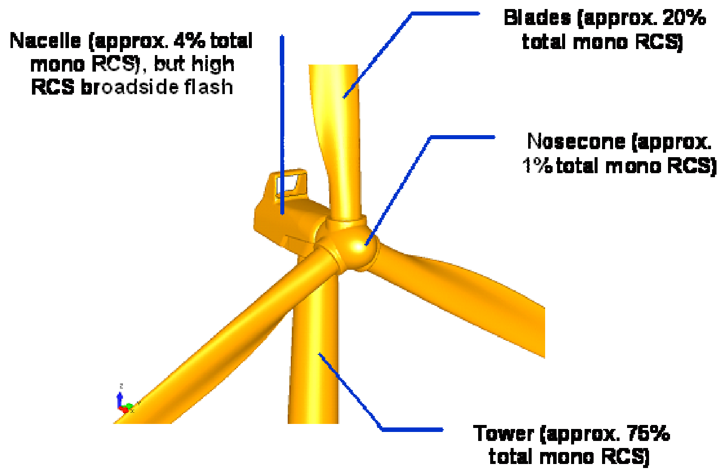

Figure 6.1: Contribution to RCS from each Turbine Component

It was concluded that the levels of monostatic RCS reduction required (i.e. 20dBsm for the tower, 10dBsm for the blade, 15dBsm for the nacelle with the nosecone simply backed by a good reflector) were achievable and could potentially be further improved upon using shaping. The largest challenges were identified as being the need to maximise reflection losses associated with the blade design given the very limited thickness (and mass) constraints and the requirement to minimise the cost per unit area of the tower solution. However, work undertaken on tower shaping indicated that only a portion of the tower surface may require the application of RAM if a simple shaping modification is adopted. Future towers may require no material application, allowing more freedom for the solution costs for the other components.

The need to minimise cost for the tower design, due to the potentially very large surface areas involved, and the need to achieve a good reflection loss over two bands suggested the use of a simply Salisbury screen based solution. A design consisting of a polycarbonate skin on a low-loss foam core was considered to be most suitable. Such a design offers the advantage of being heat formable, lightweight and was considered to require the minimum of maintenance. It is anticipated that the panels, when applied would require some form of over-painting. The polycarbonate skin is also fire retardant and preliminary adhesive trials suggest that the material can be successfully bonded to suitably prepared metallic surfaces.

The preferred blade solution is intended to be integrated within the existing blade lay-up. A design was generated which achieved the target of better than 10dB reflection loss in both frequency bands of interest (2.7-3.1GHz for aviation including civil and defence radar systems and 9.1-9.41GHz). The design took account of the fact that the materials used in the blade construction varied throughout its structure as illustrated in Figure 6.2.

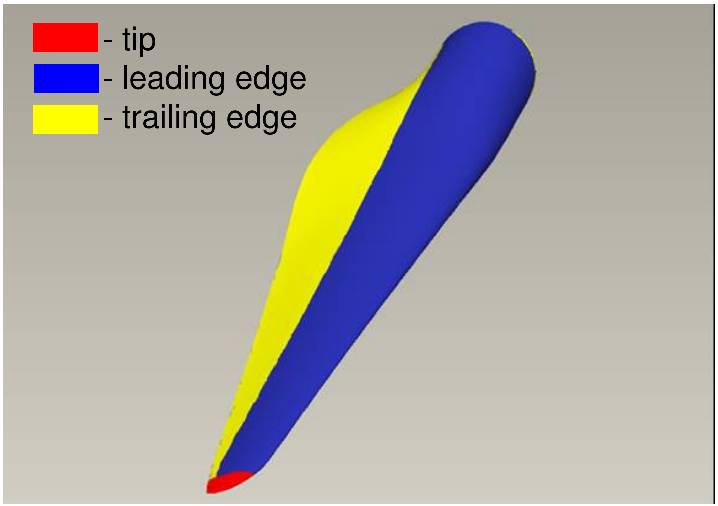

Figure 6.2: Vestas V82 Blade Geometry

RAM designs were generated for the blade leading and trailing edges. The blade leading edge treatment initially comprised of a circuit analogue based monolithic RAM design in the curved region. The trailing edge treatment was based on a Salisbury screen absorber which incorporated the balsa core material already used in the V82 blade.

The nacelle was found to have a much smaller contribution to the overall turbine RCS than the tower or blades for all angles of incidence except broadside and so is unlikely to become the dominant scatterer. The RCS for the broadside aspect may be reduced effectively by simple shaping techniques. However, a significant reduction in RCS of around 15dBsm in both frequency bands of interest is likely to be achievable using a Salisbury based solution as an alternative or supplement to shaping. The relatively small component size and low cost process used during manufacture mean that the nacelle solution is much less constrained in mass per unit area and thickness than that for other components.

6.2 Test Panel Manufacture

Test panels were manufactured for each of the solutions developed for the blade, nacelle and tower components. For the blade and nacelle components the solutions were integrated into the components by modifying the build and employing the existing manufacturing processes. However for the steel tower component it was necessary to develop a parasitic solution.

Figure 6.3 and Figure 6.4 present the measured reflection loss for the blade leading edge and mid-section test panels manufactured using a liquid resin infusion process representative of that which is used by Vestas to manufacture the blade components. Unfortunately no trailing edge test panels were manufactured. The predicted reflection loss for the blade trailing edge is therefore presented in Figure 6.5.

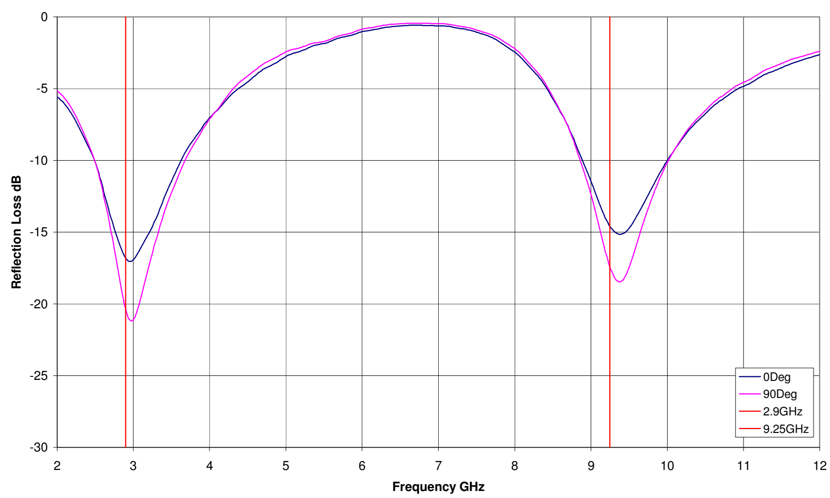

Figure 6.3: Normal Incidence Reflection Loss of Blade Leading Edge Test Panel

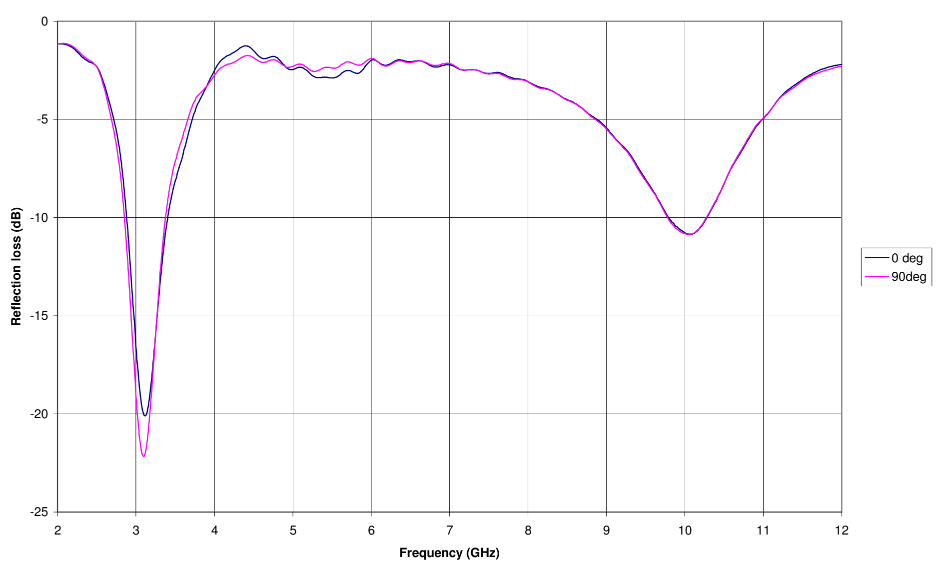

Figure 6.4: Normal Incidence Reflection Loss of Blade Mid-Section Test Panel

From the above plots it is clear that that blade test panels offer the desired reflection loss over both target frequency ranges (2.7-3.1GHz and 9.1-9.41GHz).

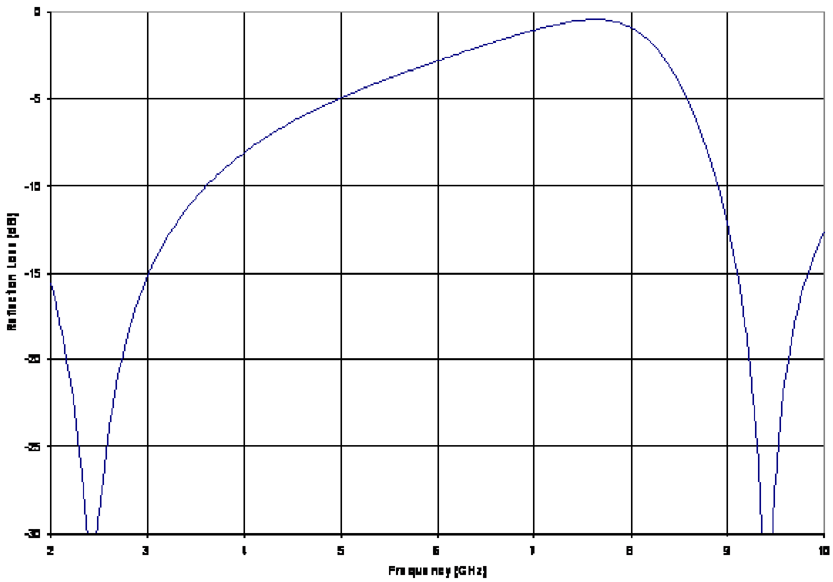

Figure 6.5: Predicted Normal Incidence Reflection Loss of Blade Trailing Edge RAM

Figure 6.6 and Figure 6.7 presents the measured reflection loss of the continuous resistive and lossy tissue based nacelle test panels respectively.

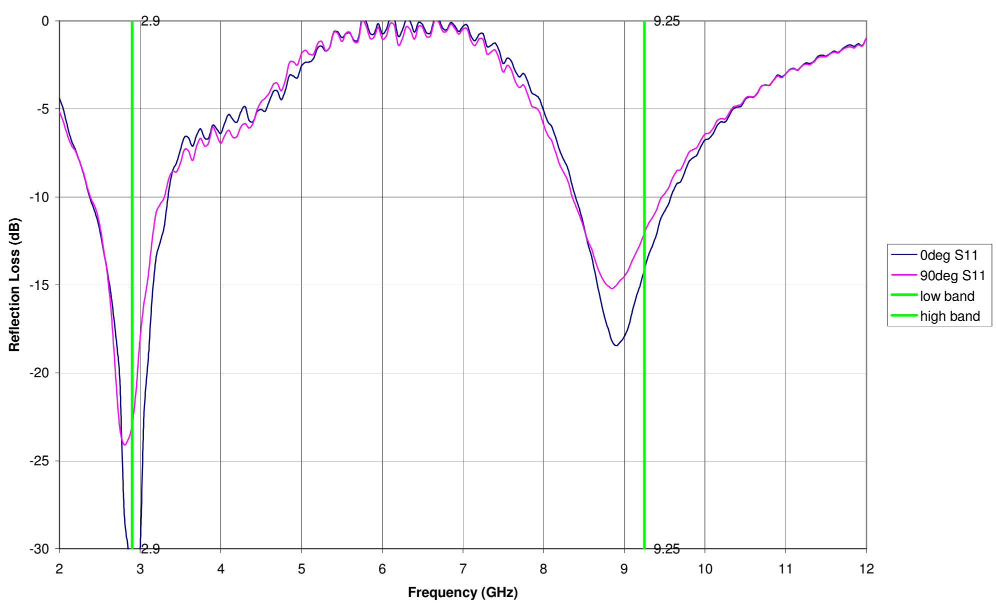

Figure 6.6: Measured Normal Incidence Reflection Loss for Continuous Resistive Material based Nacelle Test Panel

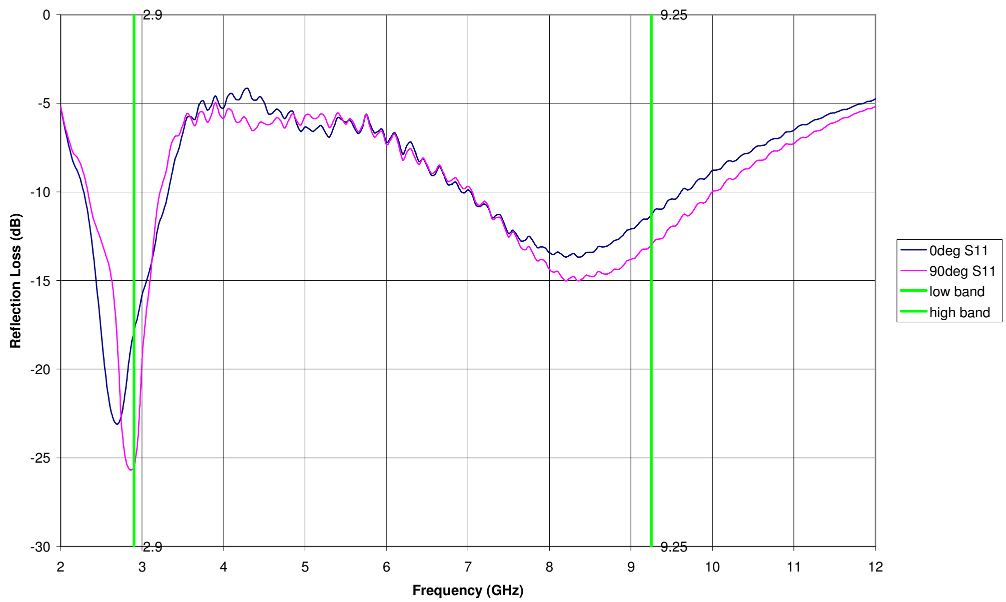

Figure 6.7: Measured Normal Incidence Reflection Loss for Tissue based Nacelle Test Panel

The nacelle panels were both manufactured using a wet lay-up composite manufacturing process which was representative of that which is used by Vestas and their sub-contractors during the manufacture of the nacelle components. It can be seen that both nacelle test panel variants offer the required reflection loss over both target frequency ranges.

Unfortunately it is not possible to include measured or predicted reflection loss data for the parasitic tower RAM. However, the test panels manufactured did provide the required reflection loss at both target frequency ranges.

Annexe B provides a summary of a lightning strike test programme undertaken on the blade test panels.

6.3 Design, Build and Characterisation of Active Test Panels

The conventional (passive) radar absorbing materials described earlier operate either by phase cancellation or by absorbing incident electromagnetic energy and converting it into heat. However, Work Package 6 of the STWT programme [12] provided some consideration to the application of novel active radar absorbing materials which are also known as phase-switched screens (PSSs). The PSS operates quite differently from passive absorbers in that it can exhibit an apparently low value of reflectivity by utilising a binary phase modulation process to redistribute the electromagnetic energy incident upon it over a wider bandwidth. If this is made very large, then little of the reflected energy will fall within the passband of the receiver. On the other hand, if the redistribution process is such that some reflected energy still falls within the receiver passband, the former is interpreted by the latter as a false Doppler shifted signal whose frequency can be changed at will by the PSS. It is this feature which indicates that a PSS could be used either to negate unwanted surface reflections or to alter Doppler signals from a moving surface such as a blade of a wind turbine.

A number of active RAM schemes were designed using CST Microwave Studio software for operation over the frequency range of 2.9 to 3.1GHz and 9.1 to 9.4GHz. The schemes were designed for to circularly (dual) polarised incident radiation and were required to provide better than -15dB reflection loss over the frequency bands of interest. For each frequency band of interest, two PSS designs were produced; one based on rigid 1.6mm thick FR4 substrate and the other on flexible 0.1mm FR4 substrate.

One metre square test panels were manufactured for each active RAM scheme. Each test panel was constructed from sixteen off 250mm square active layer tiles which were fabricated using conventional printed circuit board manufacturing techniques. The test panels were assembled by bonding the tiles to a sheet of low density rigid foam (of pre-determined thickness) which was itself bonded to a 1m square aluminium ground plane. Figure 6.8 shows an example of one of the test panel assemblies.

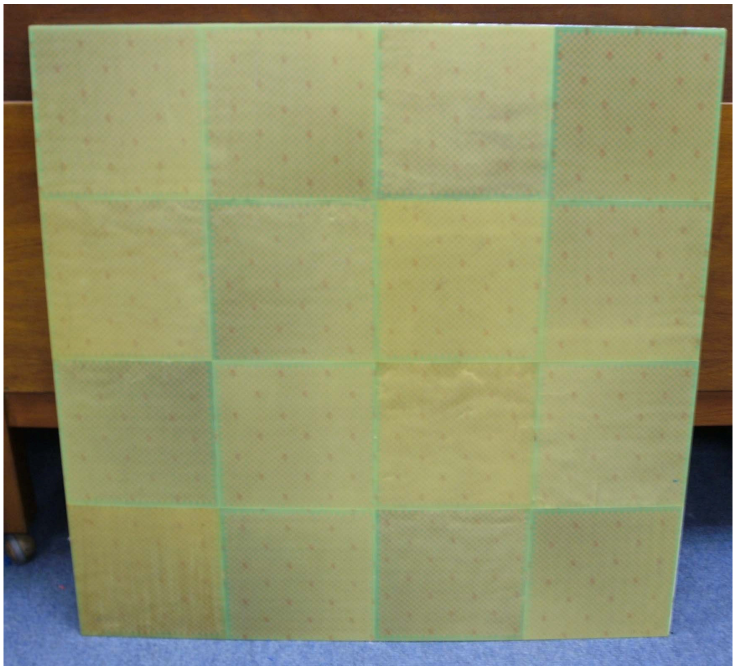

Figure 6.8: 9GHz Active RAM Test Panel using 1.6 mm FR4 substrate

The reflection loss of each panel was then measured over the frequency bands of interest with the active panels in both switched states. An example of the measured refection loss is provided in Figure 6.9 and Figure 6.10 for the 9GHz test panel with flexible substrate in the 'off' and 'on' states respectively.

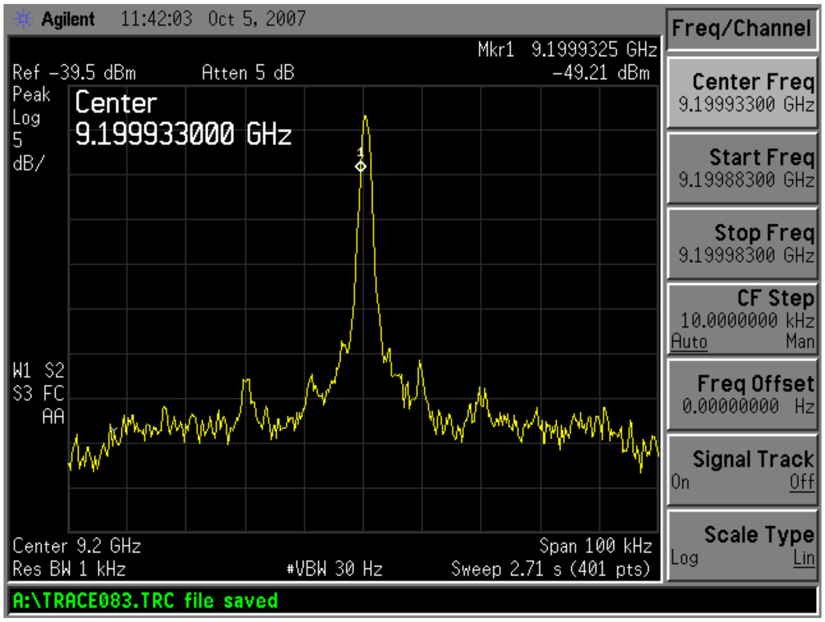

Figure 6.9: Off performance of 9 GHz Test Panel (Flexible substrate)

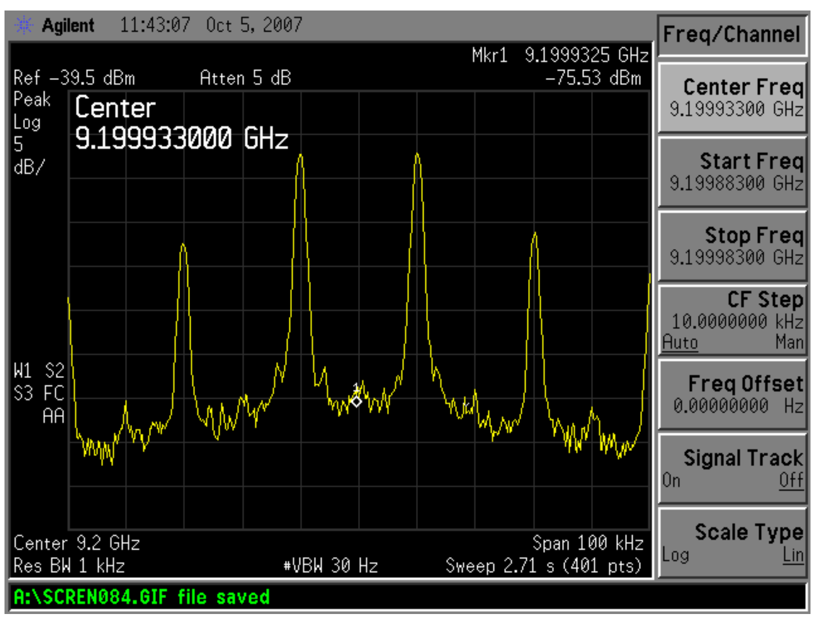

Figure 6.10: On performance of 9 GHz Test Panel (Flexible substrate)

In general the active test panels were found to exhibit good reflectivity performance over the frequency bands of interest. The work also demonstrated that it was possible to switch the 9GHz panels in order to provide a reflectivity null at either 3 or 9 GHz. The improved drapeability of the 0.1 mm flexible FR4 substrate variant is therefore a strong candidate for further development.

7 Design, Build and Characterisation of Prototype Components

This document details the work undertaken in Work Packages 12, 13 and 14 to design, build and manufacture stealthy demonstrator blade, nacelle and tower components in order to de-risk the manufacture of a complete stealth turbine.

7.1 Vestas Programme Re-scope

In August 2007 Vestas reduced the scope of its involvement in the STWT programme due to reallocation of resources and concerns about the level of redesign needed to integrate the proposed RAM design into its wood/carbon blade technology.

However, value was seen in conducting scaled down manufacturing trials on a V90 blade section to determine if further development would be beneficial and to carry out some RCS measurements. Vestas also wished to support the programme to a reasonable conclusion.

7.2 Blade Demonstrator Component

7.2.1 V90 Stealthy Blade Section Design

The previous development work undertaken in WP7 [13] had focussed on the Vestas V82 turbine. However, the trailing edges of the V90 turbine blades are manufactured using a PET (polyethylene terephthalate) foam core rather than the balsa wood core used in the V82 blades. It was therefore necessary to develop a new RAM scheme for the V90 demonstrator section. Fortunately the electromagnetic properties of the balsa were similar to that of the foam core and so the design modifications were minimal.

The risk of manufacturing a blade section which did not offer the desired RCS reductions were increased as a result of the manufacturing trials activities not being completed. It was agreed that the risks would be reduced by modifying the designs of the RAM treatments in order to make them more tolerant to manufacturing variability. However, this would lead to the final demonstrator component being only electromagnetically representative and not structurally representative of a treated blade. To achieve this, a treated blade scheme was developed based on an approximately 10mm thick solid glass fibre reinforced polymer (GFRP) based RAM design was incorporated into the blade in the leading edge and mid-blade regions and an approximately 20mm thick GFRP/balsa (sandwich) RAM incorporated into the blade trailing edge. Whilst this scheme would not be at all representative of a qualified turbine blade component, it would indicate the potential performance achievable from a stealthy blade.

It was agreed that no surface coatings (paint or gel-coat) would be included in the blade demonstrator because the electromagnetic properties of the materials used on the V90 blade had not been characterised. It would therefore not be possible to develop a blade RAM scheme which incorporated the V90 coatings. It was also agreed that the blade demonstrator section would be manufactured without incorporating a lightning strike protection scheme or any other internal (structural) features as these were below the reflective material and therefore did not affect the RAM performance.

7.2.2 V90 Stealthy Blade Section Manufacture

An approximately 2m long electromagnetically representative stealthy blade section was manufactured by Vestas using the existing V90 blade mould tools and the standard V90 blade resin infusion process [14,15,16]. The section was manufactured between 32 and 34 metres from the root end of the blade in two halves.

Unfortunately, due to an operator error during the lay-up of both halves of the demonstrator component, the carbon tissue reflector in the mid-blade region was positioned incorrectly with an additional 38mm of beech core material accidentally incorporated into the RAM design in this area. Initial modelling indicated that this was likely to completely de-tune the performance of the RAM in this region.

Feedback from Vestas indicated that the form of the resistive material was not ideal and that some modifications would be beneficial if the material was ever to be used in production components. These include;

- increasing substrate porosity to enable resin to consolidate laminate during infusion and to improve interlaminar performance.
- reducing tendency of material to curve (due to resistive layer being applied to one side only). Note that excessive spray tack adhesive was required to hold the substrate in place during lay-up.
- increasing drapeability of substrate by use of a woven fabric rather than a calendared paper in order to reduce effort required to incorporate RAM in areas of complex geometry.
- increasing resistive material sheet size in order to reduce effort required during lay-up. Note that the demonstrator section was manufactured from a number of 610mm square resistive tiles joined together during manufacture.

The two halves of the blade demonstrator section were infused and cured. When joined the blade section was trimmed at both edges in order to provide a section suitable for RCS measurement. Figure 7.1 shows the final trimmed section.

Figure 7.1: Stealthy Blade Demonstrator Section after Trimming

The blade demonstrator section was significantly thicker than a standard V90 blade section. Typically a Vestas blade manufactured using the resin infusion process would include no more than 7mm thickness of glass fibre in the leading edge but the demonstrator section was based on ~10mm thick material in the leading edge and mid-blade regions. This had a significant effect on the time taken to infuse the resin through the composite, taking 45 minutes instead of the ~20 minutes that would normally be required to infuse a standard blade section. The effect of the increased glass thickness also led to a number of dry spots on the surface of the demonstrator section where the resin failed to fully infuse the component.
Trimming of the section introduced a slight delamination within the resistive material indicating that the adhesion between the resistive material and its substrate was not adequate. This will also require consideration if am alternative substrate is to be developed for application in future stealthy wind turbine blades. Note that as a result of the adhesions issues identified here, Vestas cancelled the complete blade mechanical test programme.

Figure 7.2 shows the delamination in the trimmed edge.

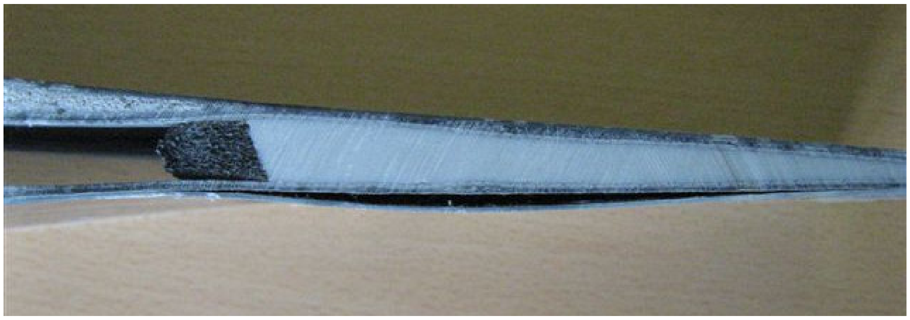

Figure 7.2: Delamination in Blade Section Edge after Trimming

7.2.3 V90 Stealthy Blade Section Characterisation

Radar Cross Section (RCS) is a measure of the energy scattered from a target following irradiation with RF energy of a given frequency or range of frequencies. It is stated commonly quoted in Decibel square meters (dBsm). A target with an RCS of $1m^2$ (0dBsm) scatters a proportion of the irradiating energy equivalent to an electrically large perfectly conducting sphere with a cross sectional area (not surface area!) of $1m^2$. In practise this is a sphere of radius 56cm. For an electrically large sphere (where the diameter is greater than a few wavelengths) the RCS can be considered to be constant with respect to frequency. For other targets, such as flat plates and cylinders, the RCS generally increases significantly with frequency.

Where possible, the RCS of a component is normally determined in an indoor anechoic chamber in order to provide a stable low RCS background which can be coherently subtracted from the target data obtained.

RCS measurements undertaken at ATC Towcester are usually carried out by rotating the samples under test about the azimuth using an automatic rotary positioner with rotational steps of 0.5°. However, due to the relatively large mass of the blade sections, the motor was unable to drive the positioner and the blade sections were therefore required to be rotated manually using a rotation step of 5° which was the minimum step size deemed reasonable given the level of effort required to complete the RCS testing.

Figure 7.3 shows the foiled demonstrator section mounted vertically in the RCS chamber prior to test.

Figure 7.3: Foiled Blade Section Mounted in Chamber

The RCS of the stealthy blade demonstrator section was measured in the ATC Towcester anechoic chamber. Figure 7.4 presents the measured RCS of the completed section with the leading edge illuminated (0° azimuth, HH polarisation).

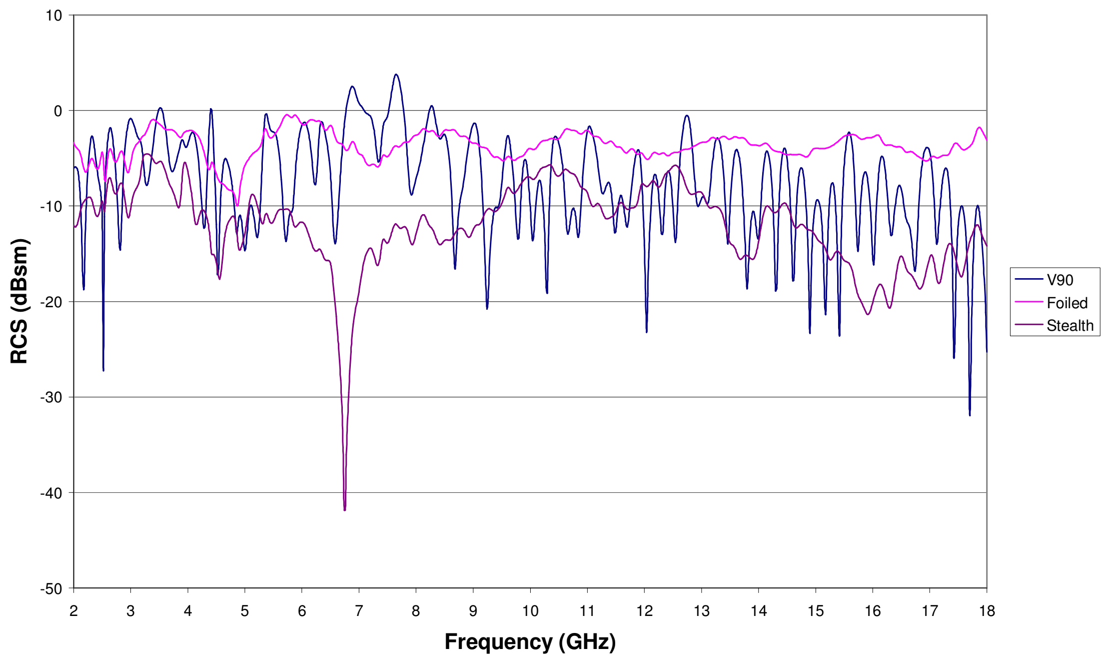

Figure 7.4: RCS of Stealthy Blade Section (0° azimuth, HH polarisation)

In order to determine the levels of RCS reduction achieved by the integration of the RAM schemes into the V90 demonstrator blade section, the data presented includes that measured for a section taken from the same position of a standard V90 blade. The plots also include data for the demonstrator coated with an electrically conducting (reflecting) foil. This data is included for information only because the initial WP3 RCS and radar modelling activities were undertaken based on the assumption that the wind turbine components were perfect electrical conductors (PEC).

Unfortunately it is not reasonable to include plots illustrating the variation of RCS with angle for a given test frequency because of the low resolution in the angular data which was caused by the 5° rotational steps making it likely that the fine structure within the data is not captured. As a result the plots would probably not provide an accurate indication of the angular variation of the RCS of the blade section(s).

From the plots it is difficult to determine whether the inclusion of the incorrect RAM scheme in the blade demonstrator mid-blade region integration has had any effect on the RCS reduction achievable. It is difficult to estimate whether the RCS performance should have shifted down in frequency or averaged out over a wider frequency range because of the lack of any significant test panel results. However, the results presented do indicate that significant levels of RCS reduction have been achieved by integrating the RAM into the blade demonstrator section. In many cases the levels of reduction exceed 10dB which was the target level identified during the requirements capture study [4].

However, the variation of RCS for the stealthy blade section with frequency cannot be fully understood because of the lack of knowledge gained during the test panel manufacturing activities. What can be said is that the RCS reductions achieved are functions of both the frequency of the incident radiation and the rotational angle of the blade. For 0° azimuth the blade section leading edge is likely to be illuminated but as the magnitude of rotation increases the mid-blade region and then trailing edge regions become illuminated. It is not possible to comment further on the contributions to the RCS reduction from each region of the blade due to the lack of available test data. However, it is reasonable to assume that the reduction levels are similar to that which would be achieved from a full blade section because for this geometry the scattering will predominantly be specular by nature.

7.3 Nacelle Demonstrator Component

The Vestas V82 wind turbine nacelle components considered in this programme are currently manufactured from glass fibre reinforced polymer (epoxy) resin using a wet lay-up process [17].

Work undertaken previously in WP3 [1] demonstrated that shaping of the nacelle is the most effective method of RCS reduction providing that the component can be made to reflect the incident radar through the application of techniques such as foiling or the application of conductive paints. However, in some circumstances the application of radar absorbing materials may be the preferred method of RCS reduction. Reference [13] provides details of the activities undertaken previously in WP8 to develop a number of different RAM treatments suitable for application in the nacelle component.

The work undertaken to date has demonstrated that both shaping and the application of RAM treatments have the potential to reduce the RCS of the nacelle component sufficiently based on the requirements captured earlier in the programme [4]. Further to this, the application of either technique is simple given the relatively trivial processes employed in the manufacture of the nacelle component. Shaping techniques can be employed by modifying the geometry of the component tooling whilst RAM treatments can be integrated into the component by modifying the build of the materials used within the component. The manufacture of a stealthy nacelle demonstrator component section was not undertaken within the STWT programme as the application of both RCS reduction techniques were deemed low risk for this component.

7.4 Tower Demonstrator Component

As with the nacelle, the preferred mechanism for RCS reduction of the tower is through shaping. However, in the case of the Vestas V82 tower studied during the programme, this constitutes by far the most significant source of scatter from the turbine, accounting for around 75% of the monostatic returns. The WP10 report [18], describes a method for significantly reducing the tower RCS through shaping, potentially very effectively and in both the frequency bands of interest. However, shaping is only viable for future turbine designs and is not necessarily regarded as a complete solution for the tower in itself. A need for an effective RAM solution was identified during the requirements capture phase for existing turbines where stealth might be required to be retro-fitted, or as a supplement to shaping where this option was limited. For example, the modification of a simple cylindrical turbine tower to that of a truncated cone can result in significant RCS reductions. However, in the case of particularly tall towers, the required slope angle may, for these cases, result in a design with a base diameter exceeding that which can sensibly be transported by road, typically assumed to be around 4.15m. Under these circumstances, the required cone angle can be preserved by using a truncated cone for the upper section of the tower with a RAM coated squat cylinder forming the lower portion.

Complete coverage of the tower with radar absorbing materials, as might be required when the direction of illumination is unknown, such as in the case of marine navigation radars, was considered to be infeasible due to cost limitations. In particular, the surface areas associated with even modest sized turbines (800m^2 for V82) are very large and it is therefore difficult to develop RAM solutions that could be manufactured and fitted without substantially increasing the overall turbine solution cost.

Reference [7] detailed the development of a ~20mm thick parasitic RAM scheme which met the requirements captured at the beginning of the STWT programme [4]. In order to verify the performance of the RAM, a steel section was manufactured to a geometry which was representative of the Vestas V82 steel tower as illustrated in Figure 7.5.

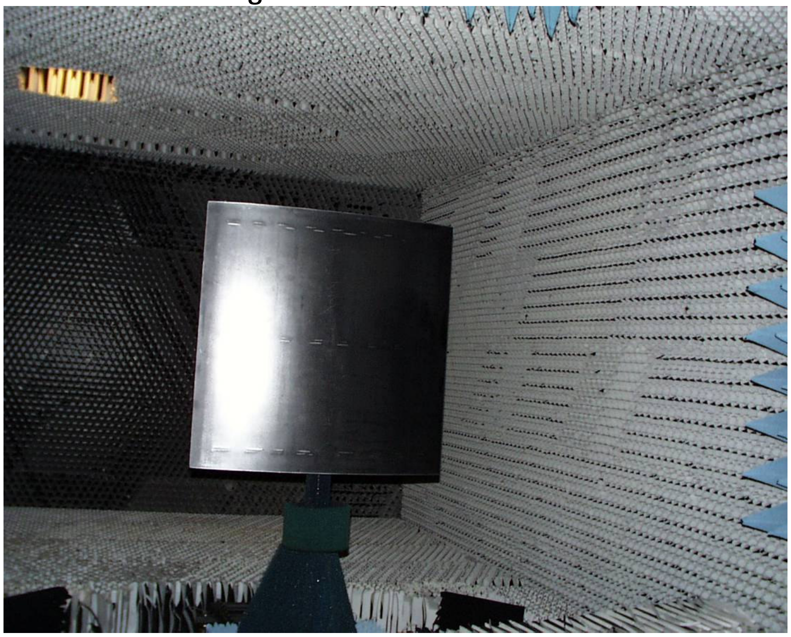

Figure 7.5: Steel Tower Section in RCS Chamber

The radar cross section of the tower section was measured in the BAE SYSTEMS ATC Towcester anechoic chamber. Following this, the section was coated with the parasitic RAM treatment developed previously and the RCS of the section was again measured. Figure 7.6 shows the treated tower section in the RCS measurement chamber.

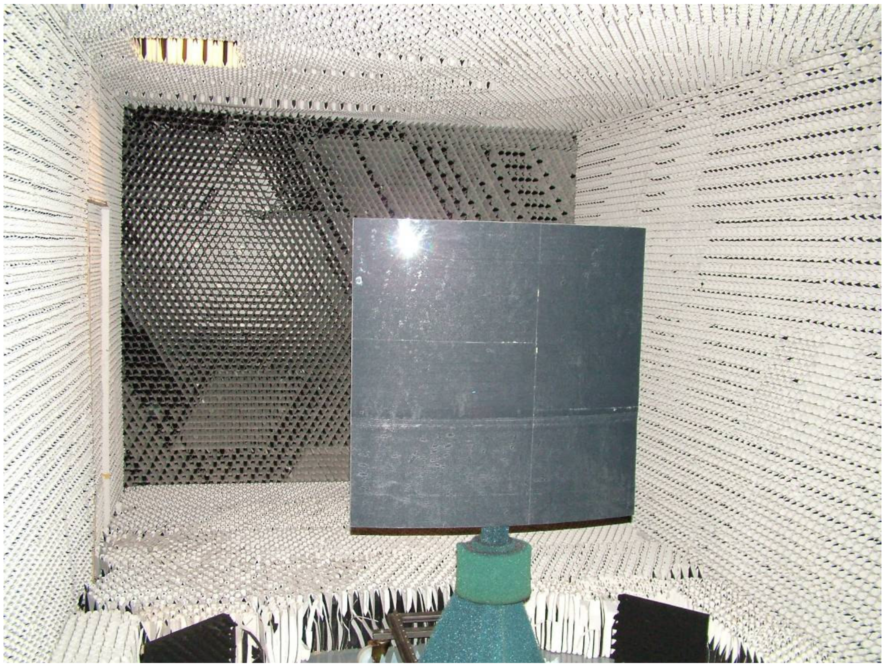

Figure 7.6: RAM Treated Tower Section in RCS Chamber

Figure 7.7 illustrates the reduction in RCS achieved for the 1m square tower section for 0° azimuth with HH polarisation.

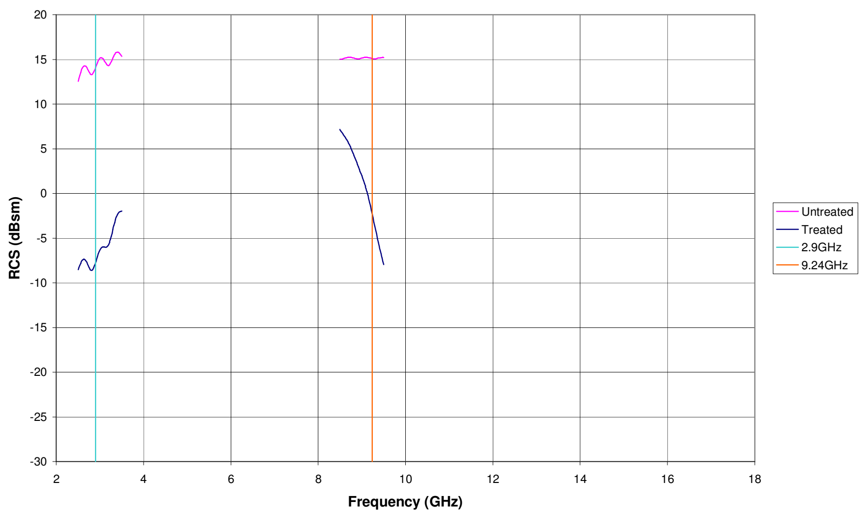

Figure 7.7: RCS data for Treated and Untreated Tower Section (HH Polarisation (0deg azimuth))

The work undertaken previously in WP9 developed a treatment that offered maximum radar absorption at 2.9GHz and 9.24GHz. However, the RCS data presented for the treated tower section indicates that in this case the maximum radar absorption is occurring at frequencies slightly higher than these original design figures. Visual inspection of the parasitic RAM undertaken after the RCS measurements indicated that the RAM treatment was slightly thinner than the original design thickness, possibly as a result of the foam core material thinning slightly when the RAM was formed to the cylindrical tower contour.

It should be noted that the data presented here is for the ~1m square tower section and that RCS levels would need to be scaled appropriately in order to determine the RCS of a treated and untreated tower component. However, for a component such as the tower where the cross section does not vary significantly over the surface of the component, the levels of RCS reduction achieved as a result of applying the RAM are representative of the levels of reduction that would be achieved when applying RAM to a full tower.

8 RCS Enhancements and Radar Impact Modelling

The modelling activities for the Stealth Technology for Wind Turbines (STWT) project were concluded by considering the integration of RAM within the blades in order to further reduce the turbine RCS. Consideration is then given to the efficacy of the combination of the proposed blade RAM treatments and nacelle and tower shaping schemes.

It should be noted that the modelling activities reported in this section were based on the RAM schemes developed for the blade demonstrator during Work Package 7 and not on those schemes actually used in the manufacture of the blade demonstrator section as discussed earlier in this report. As with the Work Package 3 activities, the radar system impact studies were shared between BAE SYSTEMS Advanced Technology Centre and the University of Manchester as follows;

8.1 RCS Modelling with Treated Blade

8.1.1 RAM Performance Data

Developing suitable RAM, which can be integrated into the existing design of the turbine blades whilst maintaining suitable performance, is a difficult technical challenge. The RAM has been optimised for maximum absorption at 2.9GHz and 9.2GHz so the same design can be used for both aviation and marine radar systems. Due to the existing blade design, it was necessary to develop two types of material, one for the leading edge/mid-blade region and one for the trailing edge. The blade regions are defined in Figure 8.1. The mid-blade region is where the lightning mesh sits underneath the surface of the blade (and, hence, this is little room for integrating RAM). Figure 8.1 also shows the four sections selected during Work Package 3 to divide the blade.

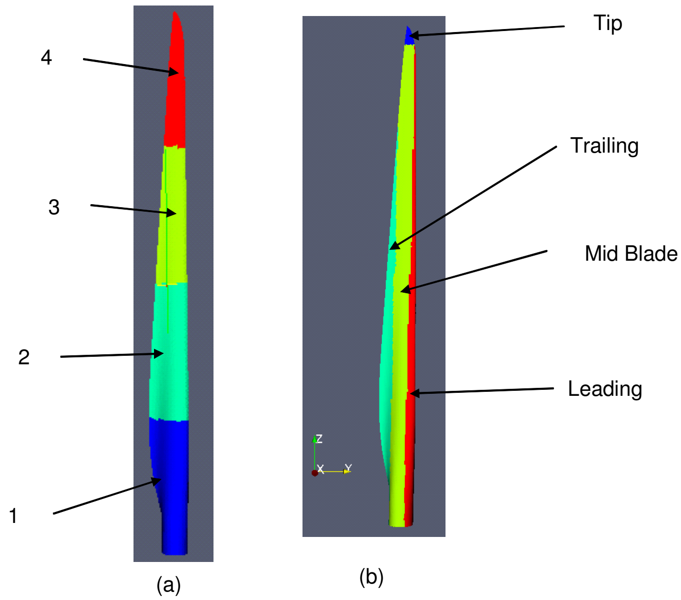

Figure 8.1: Definition of Blade Sections

The same RAM design is used for the leading and mid-blade section. To integrate the RAM into the mid-blade region, however, it is necessary add layers of GRP above the mesh to ensure a sufficient depth for the RAM design. The tip region is not treated and is assumed perfectly electrically conducting (PEC) throughout this work. Examples of the RAM reflection loss data are presented earlier in this report in Section 6.2.

8.1.2 RAM Treatment of a Single Blade

8.1.2.1 Full Treatment

The first set of results consider a fully treated blade, as illustrated in Figure 8.2 where he entire leading, trailing and mid-blade regions are treated with RAM.

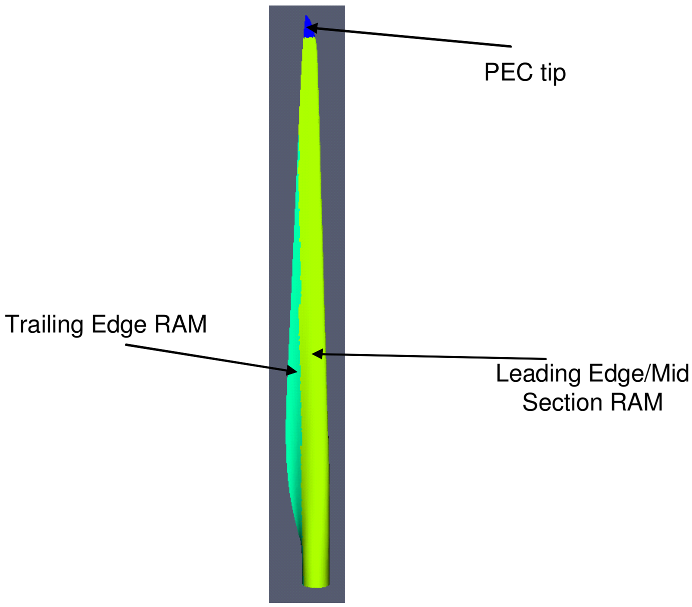

Figure 8.2: Fully Treated Blade

A comparison of the treated and untreated blade RCS is presented in Figure 8.3 and Figure 8.4 for 2.9GHz and 9.2GHz respectively. The RAM clearly demonstrates a 20dB reduction at 2.9GHz for all angles. At 9.2GHz the reduction is less than 10dB when looking at the leading edge as a result of the limitations applied to the RAM design in terms of thickness and weight.

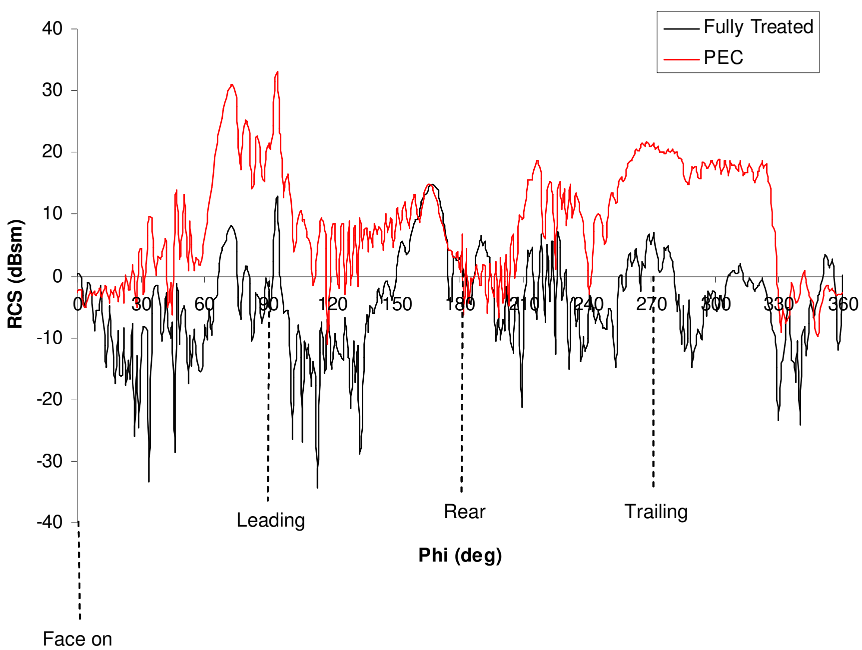

Figure 8.3: RCS of fully treated blade at 2.9GHz

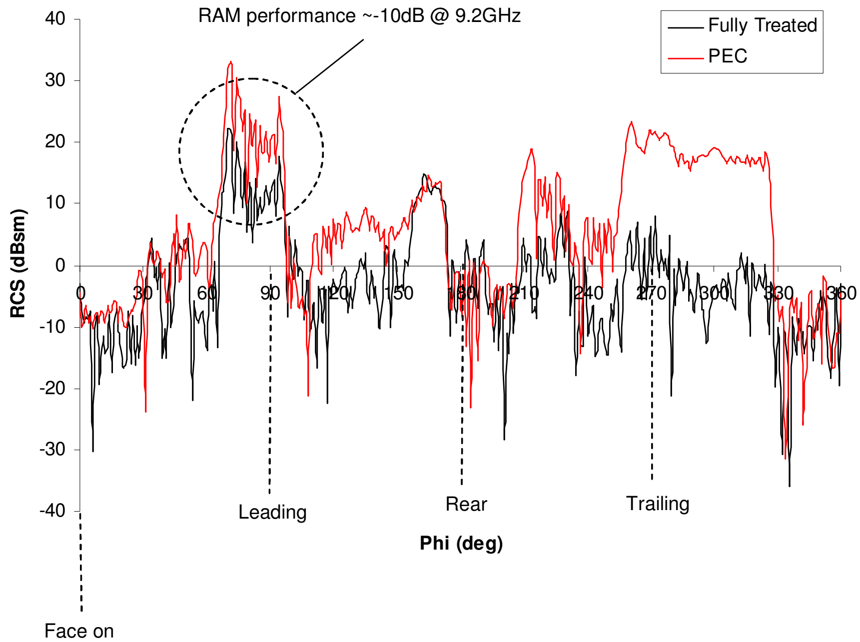

Figure 8.4: RCS of fully treated blade at 9.2GHz

The total RCS from the blade can be decomposed into sections using the divisions shown in Figure 8.1. Although not presented here, the effect of the treatment on Sections 1 (towards hub) and 2 was clearly evident with approximately 20dB reduction for all angles. The trailing edge of section 3 did not vary much compared to the untreated case but the levels are low in both cases. Section 4 (towards tip) has the least reduction of around 1-2dB compared to the maximum peak for the untreated section 4.

8.1.2.2 Partial Treatment

As discussed previously, in order to integrate RAM into the mid-blade region, above the lightning mesh it is necessary to add layers of GRP. This has an impact on the weight of the blade which is limited due to the loading on the turbine gearbox. An alternative treatment scheme was investigated to reduce the amount of RAM treatment required in the mid-blade region in order to minimise the weight increase. The scheme is illustrated in Figure 8.5 where all of the leading and trailing edge is treated but only 2/3 of the mid-blade area is covered.

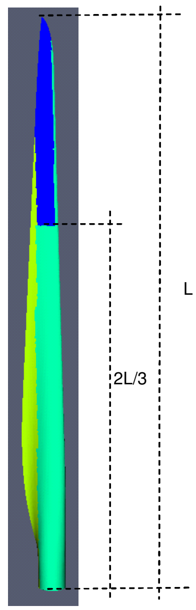

Figure 8.5: Partially Treated Blade

For the partially treated blade the RCS reductions achieved were still reasonable for the 2.9GHz case. However, at 9.2GHz, the reduction was found to be relatively poor due to the performance the leading edge RAM but still provided a reduction of 10dB.

8.1.3 Treated Turbine System

8.1.3.1 Fully Treated Turbine

In this section the RCS of a fully treated and shaped turbine is considered. All results presented in this section are at 2.9GHz, unless otherwise stated. Previously, the turbine was divided into sections, as specified in Figure 8.6.

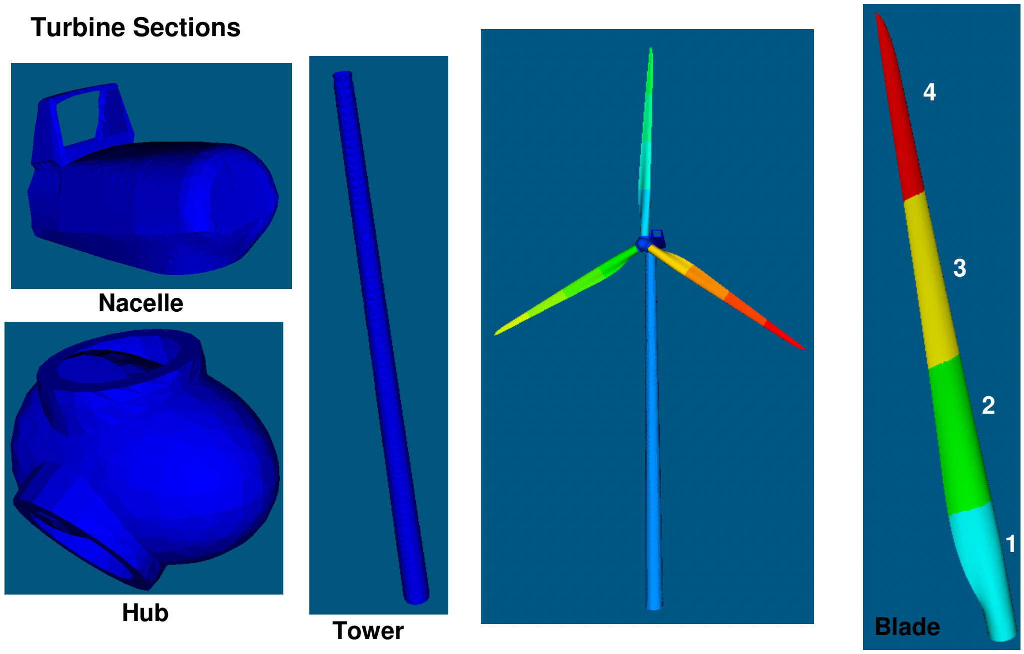

Figure 8.6: Turbine Sections

The RCS of a fully treated turbine (with shaped tower and nacelle and fully treated blades) is shown in Figure 8.7 and Figure 8.8 for the face on (yaw = 0°) and side on (yaw = 90°) case respectively. For the face-on case the RAM treatment provides a significant RCS reduction of around 20dB. For the side-on case, the blades do not dominate the response, apart from a flash from the root of one of the blades. The RAM treatment suppresses this flash, leaving the peak from the hub. For a fully treated blade the RAM treatment provides a good level of reduction.

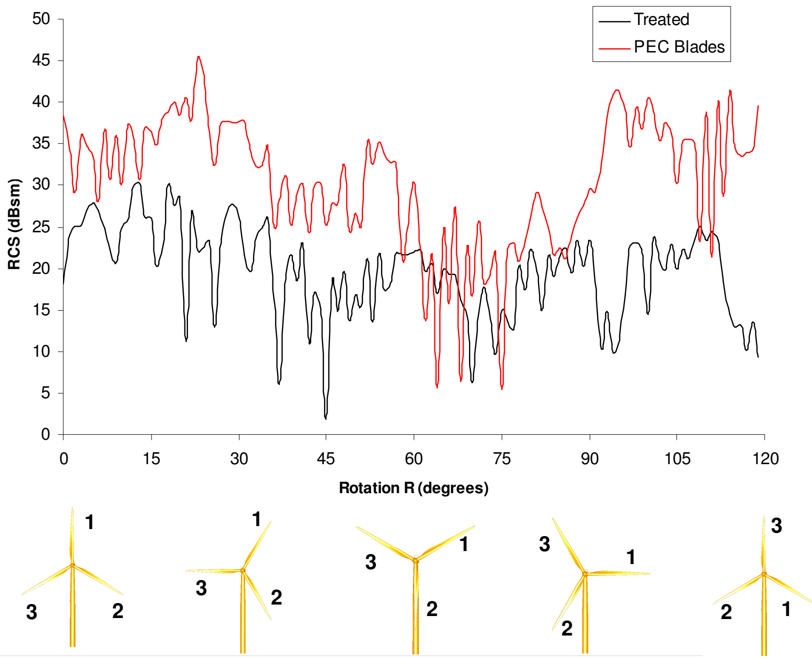

Figure 8.7: Fully treated and shaped turbine – face on

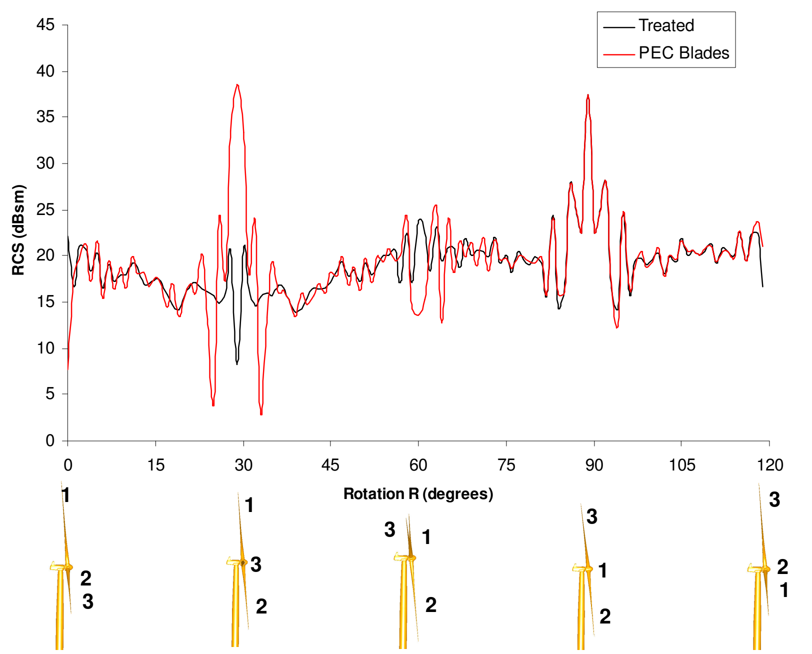

Figure 8.8: Fully treated and shaped turbine – side on

8.1.3.2 Partially Treated Blade

In Section 8.1.2.2 a treatment scheme was devised which only treated 2/3 of the mid-blade section in order to minimise the weight increases associated with the additional GRP layers required for the mid-blade section. Modelling of the entire turbine scheme indicated that the RCS peaks would not be suppressed and as a result the peak RCS would not be reduced demonstrating that partially treating 2/3 of the blade from the root end does not generate the desired RCS reduction levels.

An alternative RAM treatment scheme was devised whereby the entire length of the mid-blade region is treated across 2/3 of the width. Although not presented here, this scheme suppressed each of the RCS peaks for the face-on case leading to a total reduction of around 7dBsm.

For the side-on case, the RCS peak from the blade root is successfully suppressed sufficiently that the mean RCS is dominated by the nacelle. It is therefore unlikely that the RCS could be reduced any further by the application of RAM materials to the blades for the side-on case.

8.2 BAE SYSTEMS Impact Modelling

This section presents an extension of the work reported in Section 4.3.1 which examined the impact of the Crystal Rig II wind farm on the AR320 air defence radar system base at Brizlee Wood in Northumberland. During this work a MATLAB application, Aeolus, was developed under contract to examine the interaction between wind farms and radars. The wind farm radar cross-section data used to predict the radar system performance has been updated to reflect the updated turbine shaping considerations. In addition, the Aeolus model is used in conjunction with the RCS data of untreated turbines and treated blades and shaped tower and nacelle to show the effect of RCS reduction on the turbine components.

8.2.1 Face on Case

8.2.1.1 Target within the wind farm

A target was placed at 73.2km which is within the wind farm. The blades in the wind farm have approximately face-on aspect with respect to the radar. The mean backscattered signal power (in blue) and the threshold level (in green) for the untreated turbines is presented in Figure 8.9 below as a function of range.

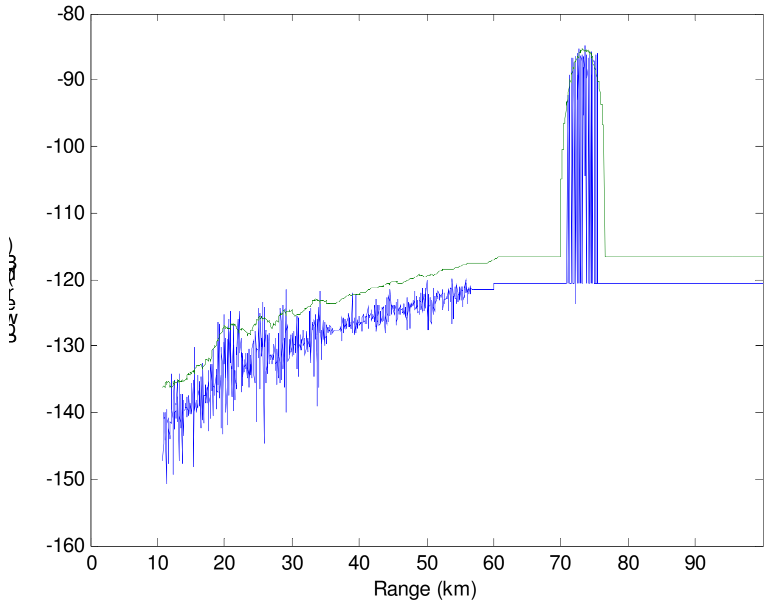

Figure 8.9: Signal power vs range; Face-on case; Target within an untreated wind farm

The target is not detectable. With the default 4dB threshold margin the wind farm is generally detected. The result for the treated turbines is presented in Figure 8.10. It is difficult to distinguish between target and wind farm detection. Raising the threshold will not render the target detectable and the wind farm undetectable. It is not, perhaps, surprising that the target is not detected since it is a demanding case. The Work Package 3 activities [1] predicted that up to 30dB of RCS reduction in the blades together with elevated thresholds was required to achieve the goal of minimising wind farm detection and with the target detected with a healthy margin. The Aeolus model was used to assess the additional reduction needed using the RCS values used in this study and it was found that a further 10dB reduction in blade RCS would achieve this goal.

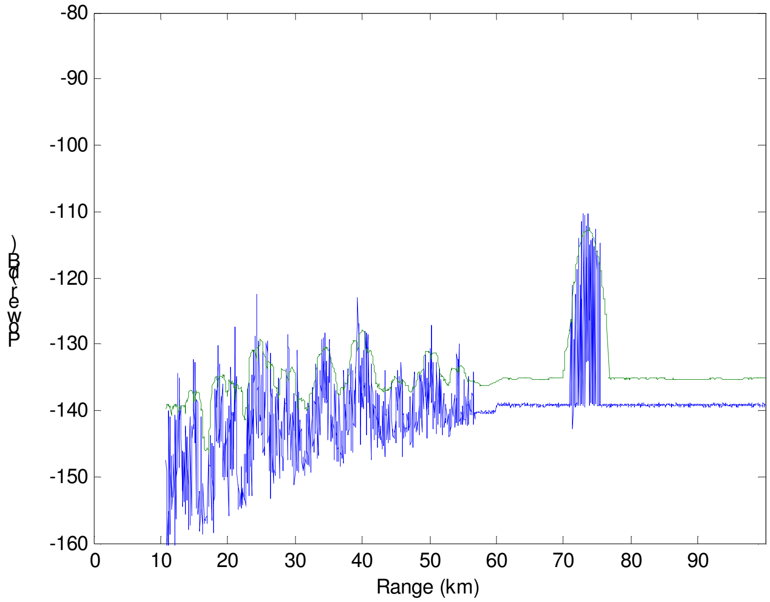

Figure 8.10: Signal power vs range; Face-on case; Target within a treated wind farm

8.2.1.2 Target within 1km of the wind farm

The target is placed at 76km range which places it outside the wind farm but within the region affected by elevated CFAR thresholds due to the close by wind farm. The mean backscattered signal power as a function of range and the threshold level for the untreated turbines is presented in Figure 8.11.

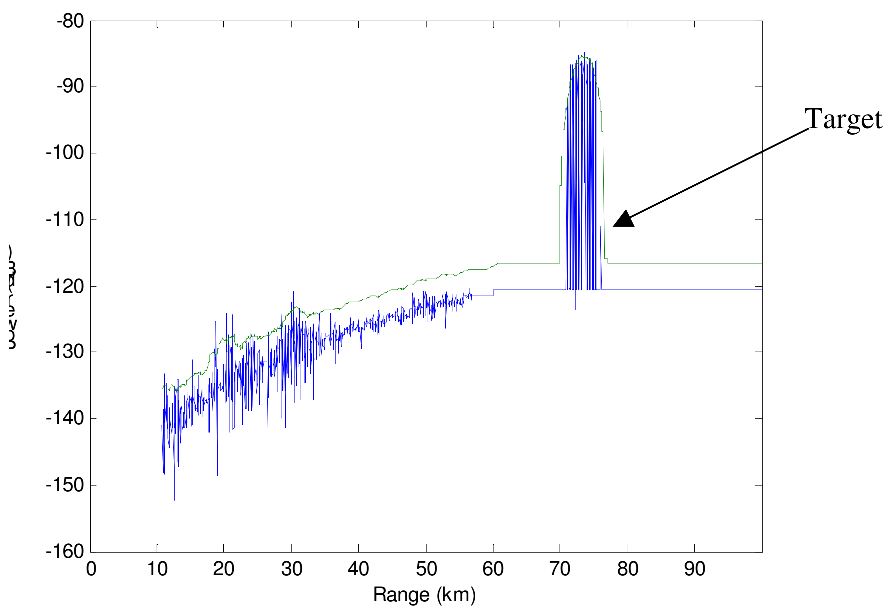

Figure 8.11: Signal power vs range; Face-on case; Target within 1km of the untreated wind farm

The target is not detectable. With the default 4dB threshold margin the wind farm is generally detected. The result for the treated wind farm is shown in.

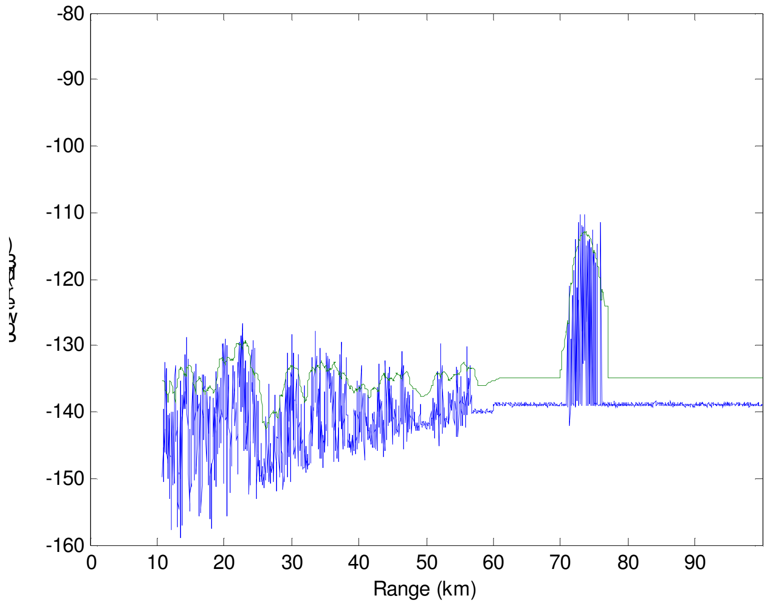

Figure 8.12: Signal power vs range; Face-on case; Target within 1km of the treated wind farm

The target is detectable with a margin of 12dB. Raising the threshold margin by a further 4dB would render most of the wind farm undetected whilst keeping detectability on the target.

8.2.1.3 Summary

Treatment of the turbines renders a reference 0dBsm target detectable in the vicinity of the wind farm. With the demanding case of a target in a wind farm, i.e. flying over the wind farm, it is predicted that treatment does not provide detectability of the target. Further mitigating options to improve radar performance for such targets appear necessary, and may include (but not exclusively):

- Achieve further reduction (>5dB) in blade RCS
- Improve MTI improvement factor – this option is limited by the blade returns which have high speed components in the Doppler spectrum of the backscatter and so are outside of the notch of the MTI (for example, increasing the MTI rejection by 10dB provides 10dB reduction of nacelle, hub and tower but provides approximately 4.5dB reduction on blade returns)

To examine the wind farm signal levels in detail Table 8.1 summarises the mean signal level for each turbine component and for the combined turbine components. For simplicity the levels are measured prior to signal processing (MTI); in general this does not affect the conclusions presented below.

	Untreated	Treated
Mean Wind farm Power (dB)	-67	**-101**
Mean Blade Power (dB)	-89	**-102**
Mean Hub Power (dB)	-113	**-113**
Mean Nacelle Power (dB)	-108	**-108**
Mean Tower Power (dB)	**-67**	**-111**

Table 8.1: Summary of wind farm backscatter signal levels; Blades face-on case

As shown, the greatest effect of treatment is on the tower which experiences a 44dB reduction in mean backscatter. The blade and nacelle components experience negligible improvement, whilst the hub is not treated and so shows no improvement. The overall mean backscatter is reduced by 34dB, the treated case being limited by the blade backscatter rather than the tower backscatter as in the untreated case. This suggests that a higher improvement factor obtained by using an MTI with deeper notch in the radar signal processing stage would not greatly influence the results since the blades, being the component with largest RCS after treatment, are not significantly attenuated by such processing. As discussed above, further reduction of the blade RCS by at least 5 to 10dB would render targets within a wind farm detectable. This would require additional treatment, over and above that examined already.

8.2.2 Side on Case

Detailed results are not presented here. However, as before, the target was found to not be detectable for the case of untreated turbines within the wind farm. Increasing the threshold margin would render the wind farm undetected but the target would remain undetected also. For treated turbines the target was found to become detectable with an 8dB margin. Some turbines were also detected, but by increasing the threshold margin by several dB these would be undetected. The target would still be detected, albeit with a small margin (5 to 6dB).

When the target is placed at 76km range it is not detected. With treatment of the turbines the target is detected with a margin of 15dB. Some turbines are also detected but increasing the threshold by 3dB would render these undetected. The target will remain detected with a healthy margin of 12dB above the threshold.

8.2.2.1 Summary

Treatment of the turbines renders a reference 0dBm2 target detectable in the vicinity of the wind farm and also in the wind farm. The latter, demanding, case provides detectability of the target with a small margin. Improvements in the assumed radar signal processing may provide a larger margin for more guaranteed detection (i.e. allowing for fluctuations in target RCS principally).

The wind farm signal levels are presented in Table 8.2, summarising the mean signal level for each turbine component and for the combined turbine components. As before, the levels are measured prior to signal processing (MTI).

	Untreated	Treated
Mean Wind farm Power (dB)	-68	**-102**
Mean Blade Power (dB)	-102	**-110**
Mean Hub Power (dB)	-109	**-109**
Mean Nacelle Power (dB)	-84	**-103**
Mean Tower Power (dB)	**-67**	**-113**

Table 8.2: Summary of wind farm backscatter signal levels; Blades face-on case

The greatest effect of treatment is on the tower which experiences a 46dB reduction in mean backscatter. The nacelle experience 19dB reduction, the blades experience 8dB reduction whilst the hub is not treated and so shows no improvement. The overall mean backscatter is reduced by 34dB, being limited mainly by the nacelle backscatter rather than the tower backscatter as in the untreated case. The hubs and blades have similar total backscatter levels after treatment (of the blades).

8.3 University of Manchester Impact Modelling

Work undertaken at the University of Manchester during Work Package demonstrated the effect of the reduced RCS turbines on marine radar systems. As with the BAE SYSTEMS impact study, the work followed on from the modelling activities undertaken in Work Package 3, where the University of Manchester built a radar propagation model to simulate the effect of wind turbines on marine navigational radars. The work modelling was based on the BAE Systems ATC's predicted RCS of both treated and untreated turbines. As before, the stealthy turbine was based on the Vestas V82 turbine with shaped tower and nacelle components and with RAM integrated into the blade.

As before, the aim of the work was to ascertain the effectiveness and the benefits of treating the current generation of wind turbines with stealth technologies by removing or reducing the unwanted effects such as the target spreading, sidelobe detection and the appearance of ghost targets.

8.3.1 Modelling Parameters

The modelling activities undertaken by the University of Manchester were based on two offshore wind farms; the existing North Hoyle wind farm and the London Array wind farm which is currently in development.

For this work, the interference of wind farms and marine radar is modelled based on the available information regarding the common radar configuration and the turbine geometry. The modelling used the measured pulse shape of a Raymarine radar using the long pulse setting (1200ns) as detailed in Annexe C. However, since some of the information regarding the radar systems in use are commercially sensitive, some assumptions are made regarding the beam shape and other radar parameters. The modeling parameters used are shown in Table 8.3.

Parameter	Setting
Gain	29 dB
Transmit Peak Power	25 kW
RF Frequency	9.4 GHz
PRF	800 Hz
Radar Height (ASL)	15 m
Pulse Length (measured)	1200 ns
Sea State	2
Rain Fall Rate	0 mm/h
Turbine Type	Vestas V82

Table 8.3: Radar System Modelling Parameters

8.3.2 Impact Prediction Results

The results of the modelling are presented in a series of PPI screenshots captured from the radar model for both the North Hoyle and London Array wind farms. The North Hoyle modelling activities were used to assess the reduction of the unwanted effects and to act as a bench mark for the remainder of calculations.

Figure 8.13 shows a PPI plot from a real ship within the North Hoyle wind farm.

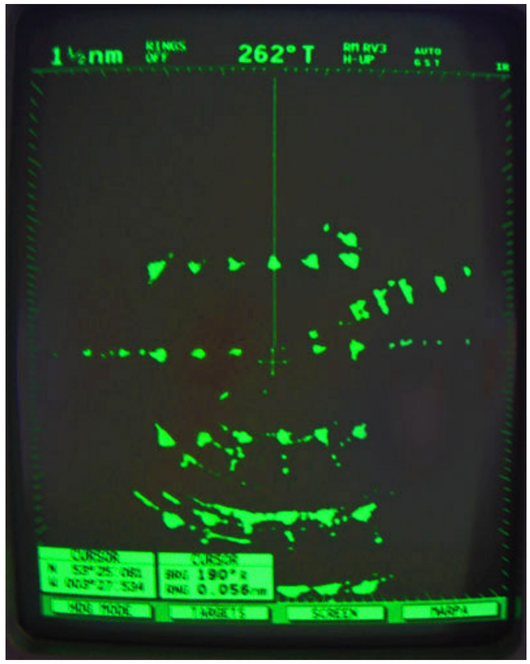

Figure 8.13: PPI image from Ship Borne Radar within North Hoyle Wind Farm

Multiple reflections within the wind farm appear to cause spurious ghost targets to appear on the radar display. The same scenario was modelled and the results are presented in Figure 8.14 where again the effects of multiple reflections of radar signals within the wind farm and some sidelobe detection are observed. The threshold level illustrated in the modelled scenario is slightly lower than that of the measurement enabling more of the unwanted effects to be observed.

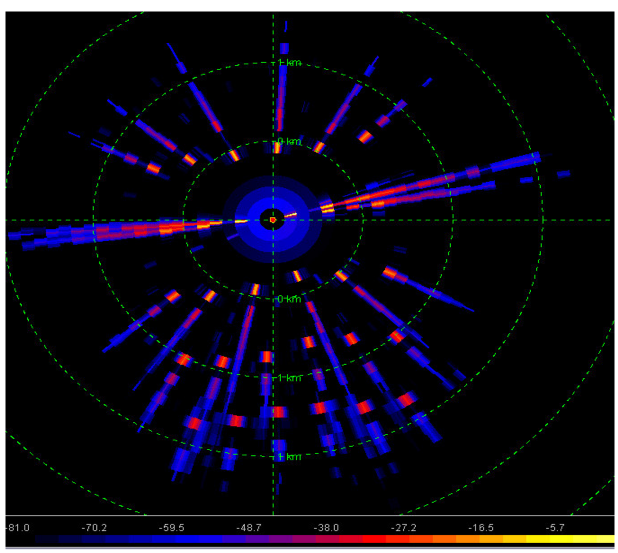

Figure 8.14: Simulating the North Hoyle farm using untreated turbines

The use of reduced RCS turbines with in the model demonstrated a significant reduction in the returns from the farm as shown in Figure 8.15. The appearance of the ghost targets is no longer a problem and no sidelobe detection can be seen.

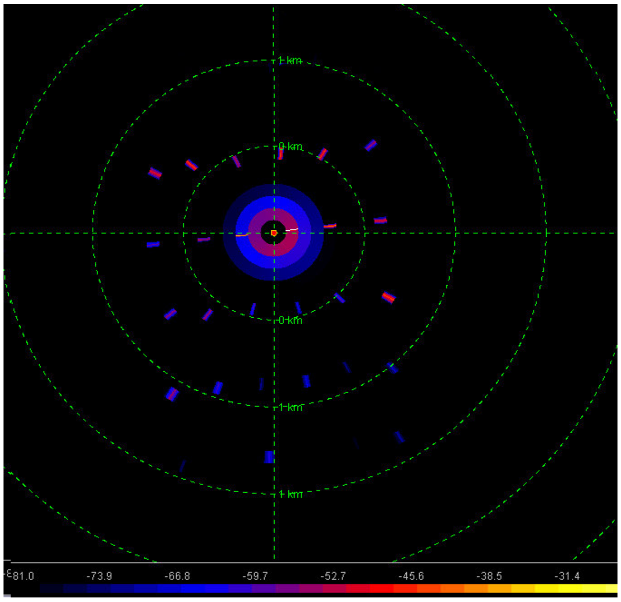

Figure 8.15: Simulating the North Hoyle farm using treated (stealthy) turbines

With the ship very close to the wind farm ghost targets appear on the radar display and some target spreading is evident in the real measured data as presented in Figure 8.16.

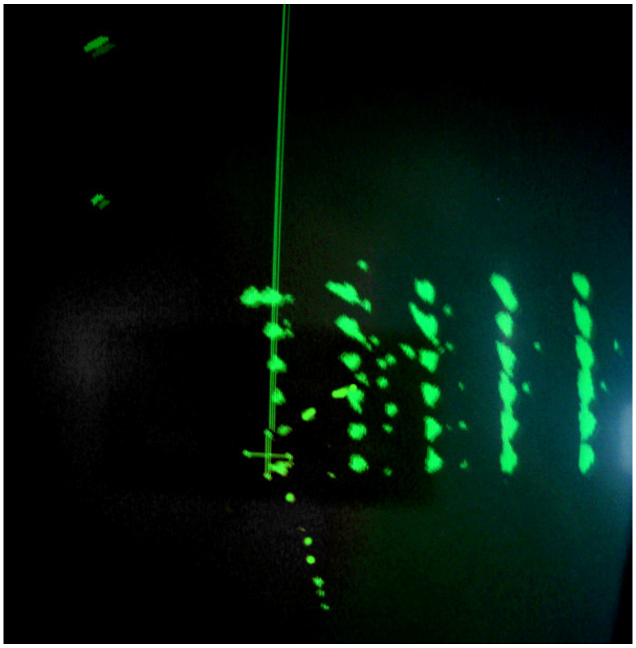

Figure 8.16: PPI image from Ship Borne Radar close to Hoyle Wind Farm

Figure 8.17 presents a simulation of the same scenario using the radar model with untreated turbines. Similarly, the effects of multiple reflection and sidelobe detection are present. However, since the beam shape used in the model is not the same as that of that used in the measurements, some differences are observed regarding the degree of target spreading. The threshold level illustrated is the same as for scenario presented previously.

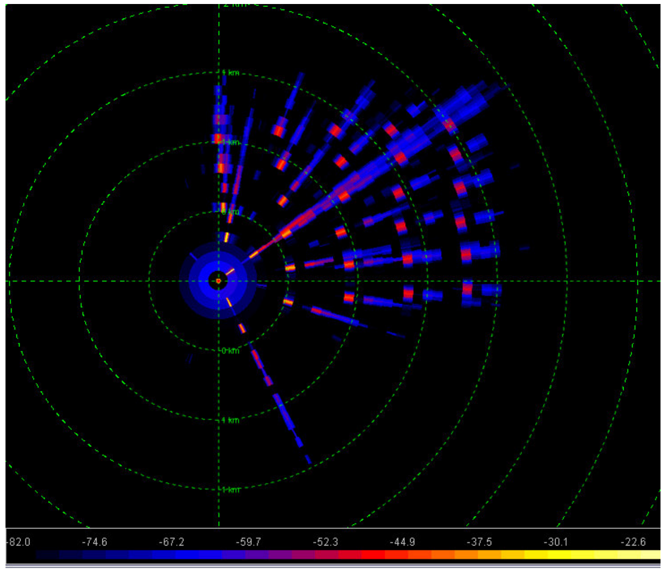

Figure 8.17: Simulated PPI plot for Ship Borne Radar close to Hoyle Wind Farm

The application of reduced RCS turbines to the model leads to a significant reduction in the returns from the wind farm as shown in Figure 8.17. There are no ghost targets and no indication of any sidelobe detection.

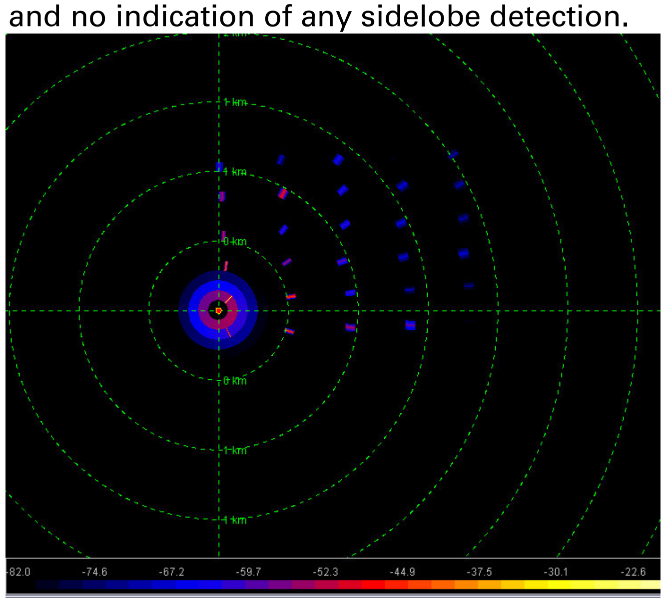

Figure 8.18: Simulated PPI plot for Ship Borne Radar close to Hoyle Wind Farm with Treated (Stealthy) Wind Turbines

Similar results were obtained for the London Array simulation as shown in Figure 8.19 and Figure 8.20.

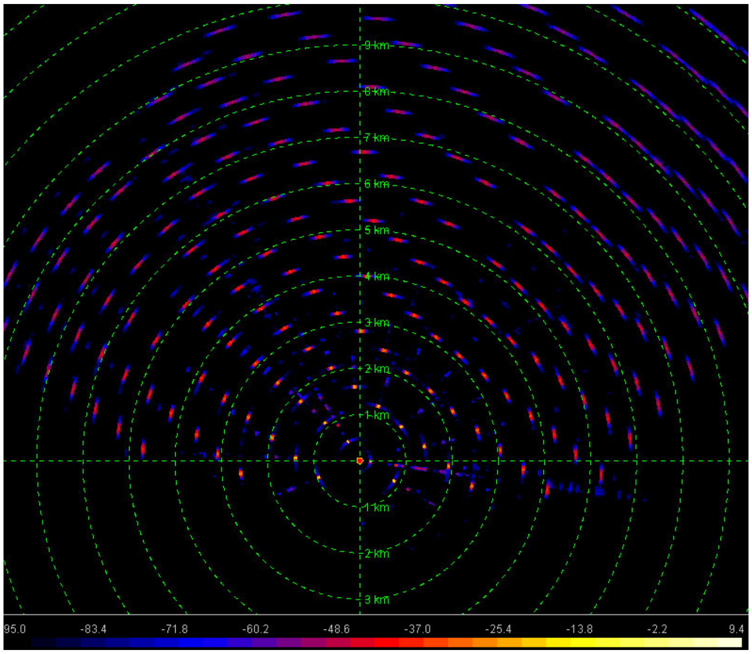

Figure 8.19: Simulated PPI plot for Ship Borne Radar within London Array Wind Farm

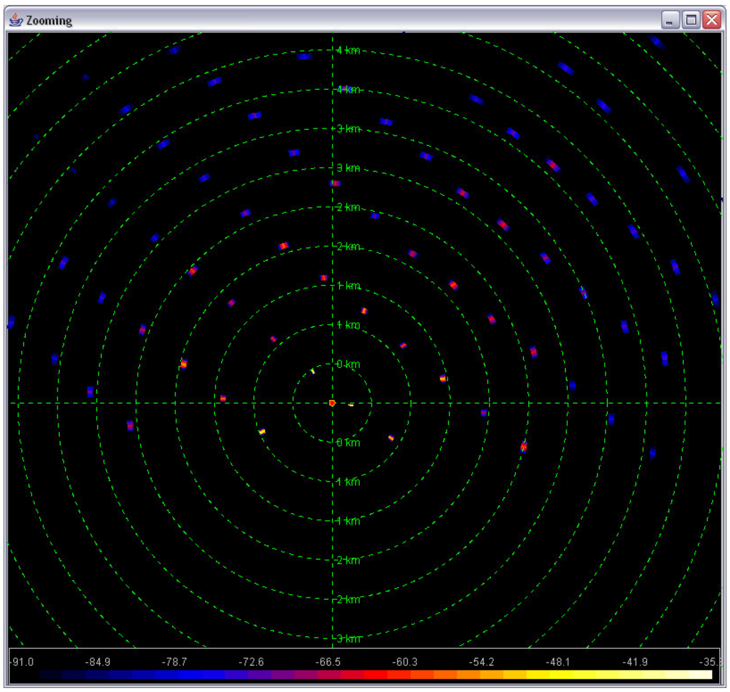

Figure 8.20: Simulated PPI plot for Ship Borne Radar within London Array Wind Farm with Treated (Stealthy) Wind Turbines

In summary, the modelling work undertaken by the University of Manchester has shown that the application of the stealthy turbines appears to reduce the radar interference effects sufficiently for small marine navigational radars. However, the modelling outputs do require validation by means of comparison with measured data for a stealthy wind farm installation. It is recommended that this be done as soon as an appropriate installation becomes available.

9 Discussion

9.1 Introduction

The large scale rejection of planning applications on the basis of interference with radar systems is a significant problem in the UK. These issues combined with a growing overseas market mean that wind turbine manufacturers and developers are starting to focus their business elsewhere in Europe and the rest of the world where there are currently fewer constraints. If the UK is to achieve its targets for renewable energy take-up then it must either relax the existing wind farm planning constraints, which is considered unlikely, or stimulate development of lower RCS ('radar compatible') turbines. The STWT programme was established to help address this by reducing the large radar signature of individual wind turbines through a combination of materials and shaping techniques in order to reduce the overall RCS of a wind turbine, including the blades, nacelle and tower.

The project objectives were to;

(i) identify the major RCS contributions from a turbine and understand which (in terms of overall RCS reduction versus cost) would most benefit from treatments and/or shaping

(ii) develop appropriate RCS treatments for the tower, nacelle and blades through a combination of turbine modelling, shaping, absorbing or reflecting materials design

(iii) demonstrate practical implementation of commercially viable RCS reduction techniques by the manufacture and characterisation of a representative blade, tower and nacelle section in order to de-risk a total turbine solution.

At the start of the programme it was agreed that the focus would be on the Vestas V82 turbine which was developed primarily to exploit areas of low to medium wind levels as are often found within the UK.

9.2 Requirements & Target Costs

During the Work Packages 1 and 2 activities [4] information was collected in order generate a concise set of requirements to assist the design of a reduced radar signature wind farm. General information which might have an impact on the application of aerospace stealth technology to wind farms was also collected such as typical manufacturing methods for various components and reasons behind particular wind turbine layouts in a farm. Unclassified performance data on a range of radars operated by parties who have raised objections were also collected and published where commercial and security issues permit.

The development of a single RAM solution incorporating additional frequency bands, particularly at lower frequencies such as that used by the AN-FPS117 AD radars operated by the UK Royal Air Force was not considered feasible for the turbine blades due to the requirement to minimise the increase in blade thickness and weight. However, it was considered feasible to develop single band solutions at different frequencies to address specific stakeholder problems on a case by case basis.

Following capture of the main requirements it was agreed that the STWT programme should focus on developing dual band shaping and RAM solutions which cover the frequency ranges of 2.7-3.1GHz and 9.1-9.41GHz in order to generate a solution which would help address a significant proportion of the existing planning application rejections. It was noted that significant reflection losses over both these bands may be achievable by the application of RAM but for the blade components any solution would probably be compromised by the thickness and mass constraints imposed by the manufacturing process, where there was a requirement to preserve the existing external geometry in order to maintain aerodynamic and structural performance. It was considered likely that these additional constraints would have the largest impact on the effectiveness of the candidate solutions. This was particularly so for the Vestas blades based on the materials in their construction and the process used during manufacture.

The constraints identified for the tower and nacelle components were less stringent enabling greater freedom in the design and application of RAM materials. However, the tower and nacelle were also both identified as ideal candidates for RCS reduction through shaping which was agreed to be the better solution.

9.3 Initial RCS and Radar Modelling

Work undertaken during Work Package 3 included modelling the RCS of a wind turbine and the development of radar system simulation models for assessing the impact of wind farms on radar systems. The radar system modelling activities were shared with BAE SYSTEMS Advanced Technology Centre considering an onshore wind farm and the University of Manchester considering an offshore wind farm. The development of the radar system models at an early stage was important in order to determine the levels of radar cross section (RCS) reduction required to significantly reduce or remove the radar interference issues caused by a wind farm.

The work undertaken by BAE SYSTEMS ATC also considered modelling the monostatic RCS of a wind turbine. Results for each Vestas V82 wind turbine component (blade, nacelle, nosecone and tower) were simulated at 3GHz and

10GHz as a function of blade rotation angle and yaw angle in order to determine the major radar scattering sources. The results were combined to generate RCS data for the entire turbine structure where scattering from the tower accounted for approximately 75% of the total turbine RCS depending on the frequency of the incident radiation, illumination angle and turbine configuration. The V82 nacelle was found to have a monostatic RCS which was generally lower than either the untreated tower or blades, except for the side on case (90° yaw) where the broadside flash from the flat sides of the nacelle resulted in significant levels of backscatter. The RCS of the nosecone was found to typically constitute only around 1% of the overall scattering from a turbine and so no RAM solution was deemed necessary, except to ensure that the material from which it is fabricated is backed by a microwave reflector.

The BAE SYSTEMS ATC radar model was used to predict the impact of the Crystal Rig II wind farm on the Type 93 Air Defence radar situated at Brizlee Wood. Similarly, the University of Manchester model was used to simulate the effect of the North Hoyle wind farm on a small ship borne marine navigational radar system. Both models considered the wind turbines with and without RCS reduction. Both codes indicated that overall RCS reductions of approximately 20dBsm would be enough to substantially reduce or eliminate the undesirable interference effects from a wind farm thereby indicating that stealth material and shaping technologies do have the potential to mitigate the interference issues which currently are the basis for a large number of wind farm planning application rejections in the UK.

A cross-validation exercise between the two radar system models indicated general agreement between the results for a single scenario. However, further work is still required in order to fully validate the codes including comparison of the model outputs with measured data.

9.4 RCS Reduction through Shaping

The feasibility of the application of shaping in the reduction of the RCS of a wind turbine had previously been identified for the nacelle and tower components. A number of modelling activities were therefore undertaken to establish if the levels of reduction achievable were in line with the requirements identified during the radar system modelling activities for the Vestas V82 turbine.

The optimum geometry for the V82 tower was identified as being a truncated cone. Within the constraints set to allow transportation of the tower, a base diameter was chosen which minimised the RCS at both target frequencies simultaneously. For the face-on (0° yaw) the turbine RCS was reduced by around 10dB leading to the blades becoming the dominant RCS scatterers. For the side-on case the RCS was reduced by approximately 15dB causing the nacelle to dominate the RCS.

The nacelle was shaped by the application of facets to the main scattering sources leading to a total reduction in RCS of approximately 20dB. The total RCS of the complete turbine with shaped nacelle and tower was reduced by around 30dB for the side-on case. However, for the face-on case it was still dominated by the blade RCS. Consideration was therefore given to the application of a RAM treatment to the blades in order to further reduce the RCS of the whole turbine as discussed below.

9.5 RAM Development

A number of different RAM schemes have been developed for application in the blade component based on the current manufacturing processes. However, treatment of the component is not trivial due to the fact that the blade is split into several regions. The solution generated for the blade leading edge can be integrated without too much difficulty but the mid-section design was likely to cause a significant increase in the thickness of the design and the weight of a blade component. Whilst this was undesirable, preliminary discussions with Vestas indicated that these increases could be accommodated within the current V82 blade without the need for a re-design or an additional structural qualification activity.

The successful design and manufacture of a number of blade RAM test panels demonstrated that the integration of the RAM schemes within the blades would be achievable. However, the work also highlighted a number of limitations of the blade manufacturing processes which would have some impact on their application in the manufacture of radar absorbing structures including control over the moulded thickness and fibre/resin volume fraction, both of which are parameters which influence the electromagnetic properties of the final component.

As discussed previously, shaping was identified as the preferred method for achieving RCS reduction in the tower and nacelle components. However, RAM schemes were developed for both the tower and the nacelle components as part of the programme for application in specific circumstances such as where shaping is not possible due to other design constraints or, for the case of the tower, where existing turbines are to be treated retrospectively. The tower RAM scheme was based on a lightweight, durable and relatively low cost parasitic material which could be heat-formed and bonded directly to the steel tower components. A small amount of surface preparation would be required prior to bonding but the processes used to manufacture the tower components would not need modifying.

For the nacelle component two different RAM schemes were successfully developed based on the existing wet lay-up manufacturing process. The first was based on a modified Salisbury screen and the second on a dual layer Jaumann absorber.

9.6 Design, Manufacture and Characterisation of Demonstrator Components

Discussions held with the Vestas tower manufacturers identified that the application of shaping to reduce the RCS of a tower component would not involve any significant changes to the current tower manufacturing processes. The tower demonstrator manufacturing activities therefore focussed on the application of the tower RAM to reduce the RCS of the tower component. A steel section representative of a tower section was manufactured and its RCS properties characterised with the external surface exposed and with a parasitic RAM fitted. Analysis of the results indicated that the application of the RAM provided the required reduction in the component's RCS. However, the performance was shifted slightly up in frequency, probably as a result of the structural foam core thinning during the heat-forming.

The manufacture of a nacelle demonstrator component section was not undertaken within the STWT programme as the application of shaping and the integration of RAM were deemed low risk for this component given the materials and processes used to manufacture the nacelle components.

The value in manufacturing the blade demonstrator section was reduced significantly as a result of Vestas reducing their contribution to the STWT programme including the termination of a number of the development activities. However, a 1.85m long electromagnetic representation of a stealthy blade section was manufactured based on a Vestas V90 blade rather than the V82 blade which the programme had originally focussed on. During the manufacture the production staff identified a number of issues associated with the resistive material which made it unacceptable for use in production components.

RCS measurements were undertaken on the blade demonstrator section but unfortunately, due to an operator error during the manufacture of the component, the RAM design was not integrated into the component as required. From the results it was difficult to determine whether this had any effect on the RCS reduction achievable. However, significant levels of RCS reduction were achieved and in many cases the levels of reduction exceeded the target of 10dB outside of the target frequency ranges. In future it is recommended that further development work be undertaken in order to ensure that the any future stealthy blade components have the best opportunity of operating over the required frequency ranges.

The design, build and characterisation of a number of schemes has demonstrated that active solutions may have application in future generations of stealth wind turbines. However, at present, a major limitation in the application of such materials is where problems arise in designing and realising the power supply output stages which are required to tolerate fast pulse rise and fall times, large supply currents and potentially large load capacitances. These problems can be dealt with to some extent by splitting the active panels into tiles, each of which is fed from its own individual power supply. However, further work is clearly required in this area to increase the technology maturity before it may find application in future wind turbines. Further work is also likely to be required in order to develop electrostatic discharge and lightning strike protection schemes which do not compromise the reflection loss performance of the active RAM.

9.7 Radar Impact Studies

The studies undertaken during this programme demonstrated that significant reductions in RCS were possible through shaping alone. However, for the face-on case, the blades dominate the RCS response. In this case, the application of RAM treatments within the blades was required to further reduce the RCS of the turbine.

9.7.1 ATC SS Impact Study Notes

The radar system impact modelling undertaken by BAE SYSTEMS ATC using the radar model, Aeolus, performed for the Crystal Rig II onshore wind farm demonstrated that the application of both shaping and RAM technologies in fully treated turbines extend the coverage of detectability of targets flying over or in the vicinity of a wind farm for the specific radar installation. With the blades side-on to the radar, the detectability extends through the whole range of radar coverage. With the blades face-on to the target detection is possible in the vicinity of the wind farm but is still compromised for a target flying over the wind farm. To address this other mitigation techniques are likely to be required such as improved signal processing by means of the BAE SYSTEMS Insyte ADT radar or similar.

In summary, the radar impact study undertaken by BAE SYSTEMS indicates that for the case study selected the treatment of the turbines through shaping and RAM provides the potential for significantly mitigating the effect of a wind farm on a nearby radar system. However, the findings indicate that the application of stealth technologies to mitigate the undesirable effects in other radar/wind farm scenarios is extremely promising.

9.7.2 University of Manchester Impact Study Notes

For the offshore impact study activities, the University of Manchester used their radar system model to provide further support to the suggestion that the RCS reduction of the turbine through tower and nacelle shaping had the biggest impact on improving the radar detection. Similarly, the modelling indicated that the application of reduced RCS turbines would result in significant reduction in the appearance of ghost targets, target spreading and sidelobe detection in small, marine navigational radar systems.

The radar impact studies undertaken by both partners indicated that the RCS reductions proposed would be sufficient to reduce the radar interference effects sufficiently for small marine navigational radars. However, it should be noted that the modelling outputs do require validation by means of comparison with measured data for a stealthy wind farm installation.

9.8 Design, Manufacture and Characterisation of Active Test Panels

9.9 Future Work

The programme activities were focussed on developing solutions which were feasible within the commercial cost limits identified and solutions identified for the nacelle and tower components were successful in this. However, information collected during the programme relating to the blade component was insufficient for any conclusions to be drawn against the commercial viability of the solution. This will therefore need addressing by the consortium partners in the near future if the programme outputs are to be fully exploited.

A number of other activities are required before a fully treated turbine system can be installed and evaluated. Initial activities should focus on assessing the market potential for stealth wind turbine systems both within the UK and abroad and the requirements captured within the STWT programme should be reviewed and updated if necessary. Particular focus should be aimed at the radar operators and the wind turbine manufacturers.

The issues identified with the resistive material developed during the STWT programme should be addressed and further work undertaken in order to optimise the blade RAM schemes in terms of their performance and integration of the materials into the current blade components. Consideration should be given to a number of requirements not considered during the STWT programme including both the structural and lighting strike performance of the blades. When complete, the manufacture and installation of a stealthy turbine system will enable the effectiveness of the RCS reduction techniques to be quantified and the radar system models to be validated.

9.10 Exploitation

The STWT programme has enhanced the UK technology base by developing the capability of each of the programme partners in a number of ways. BAE Systems and the University of Manchester have both developed modelling tools which have potential for exploitation to support consultancy activities in assessing whether wind farms are likely to cause radar interference problems at the planning stage. In addition, BAE Systems has obtained a significant amount of understanding regarding the integration of radar absorbing materials into wind turbine components and has generated the potential for high volume material sales. For Vestas, completion of the programme activities has provided design criteria that be can fed into future blade design activities to both reduce the RCS of the turbines and enable increased success in the incorporation of RAM into blades. This could potentially increase the market scope for future turbines in both the UK and Europe. In addition, both the University of Sheffield and the University of Manchester have increased exposure of their technical capability through the attendance and presentations at a number of high profile conferences. Further information is available in the STWT programme exploitation plan [19].

10 Conclusions

The STWT programme has addressed the major problem of the interference caused by wind farms on radar systems at the source. In addition, the programme has delivered a set of prototype turbine demonstrator components which de-risk the manufacture of a stealth wind turbine solution sufficiently to enable the development of a full size, low RCS turbine for evaluation on a trial site.

During the programme, a suite of modelling tools has been developed to help simulate the RCS of wind turbine installations and to predict the impact of wind farms on radar systems.

The programme has delivered a comprehensive understanding of the major scattering sources on wind turbines and has identified both material and design methods which can be used to minimise the impact of wind turbines on target radars. In addition, radar system modelling has indicated that the application of both shaping and materials solutions have the potential to reduce the interference effects significantly.

Shaping solutions have been proposed for the nacelle and tower components that can be implemented without introducing any significant changes to the current manufacturing processes and without adding significantly to the mass. The proposed solutions are compatible with the current methods currently used to interface between the turbine components and they do not require modification of the internal structure of the components.

A number of RAM treatments have been developed for the turbine blade components which are compatible with the tooling, materials and processes currently used by Vestas during manufacture. However, the proposed blade solution does not comply with the mass increase constraint identified during the early stages of the programme which were based on the requirement to avoid any additional blade qualification activities. Additional work is likely to be required in future in order to confirm the structural integrity of the treated blade components and to qualify them for service use.

Each of the shaping and RAM solutions take account of and comply with the known environmental requirements. However, further work is required in order to ensure that the treated blade component complies with the known lightning strike specifications. Feedback from Vestas indicates that the schemes proposed for both the tower and nacelle are commercially viable. However, further development is required in order to develop the blade schemes sufficiently to ensure that they are acceptable from a commercial perspective.

A number of recommendations for further work have been made based on gaining further understanding of the requirements of both the wind farm and radar operators. Additional work has also been recommended to further develop the blade RAM schemes in order that they are integrated into a blade component without compromising the structural integrity of the turbine. Once complete, it has been recommended that a fully treated turbine system be installed and evaluated in order to confirm the levels of RCS reduction achievable and to help validate the radar system models developed within the current programme.

Overall, the work undertaken during the programme will in future accelerate the rate of development of commercially viable low RCS turbines thereby placing the UK at the forefront of low RCS wind turbine technology.

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12 Annexe A : Comparison of Radar System Models

An exercise was undertaken to cross-validate the BAE SYSTEMS ATC and University of Manchester radar system models. The scenario selected for modelling is based on the Vestas V82 turbine and the parameters presented below in Table 12.1.

Wind farm		Radar	
Site	Crystal Rig	Site	Brizlee Wood
Height	350m	Radar type	Plessey AR320
Blade rotation rate	25rpm	Frequency	3GHz
Tower height	60m	Polarisation	Horizontal
Blade length	40m	Transmit power	60.5dB
		PRF*	250Hz
Antenna Pattern		Received b/width	250Hz
Beamwidth	1.4° (az), 1.6° (el)	Range resolution	40m
Sidelobes	35dB (az), 32dB (el)	CPI** length	10
Mast heights	4.9m	Noise figure	2.5dB
		System loss	11
		STC***	off

Table 12.1: Modelling Parameters

* PRF - Pulse Repetition Frequency
** CPI - Coherent Processing Interval
*** STC - Sensitivity Time Control

The modelling comparison assumed no multi-path propagation and no multiple bounce reflections within the wind farm. The two codes offered a number of different processing features. Power received versus range was identified as the most appropriate system output to compare. Figure 12.1 presents a comparison of the results from the two models for a one particular radius.

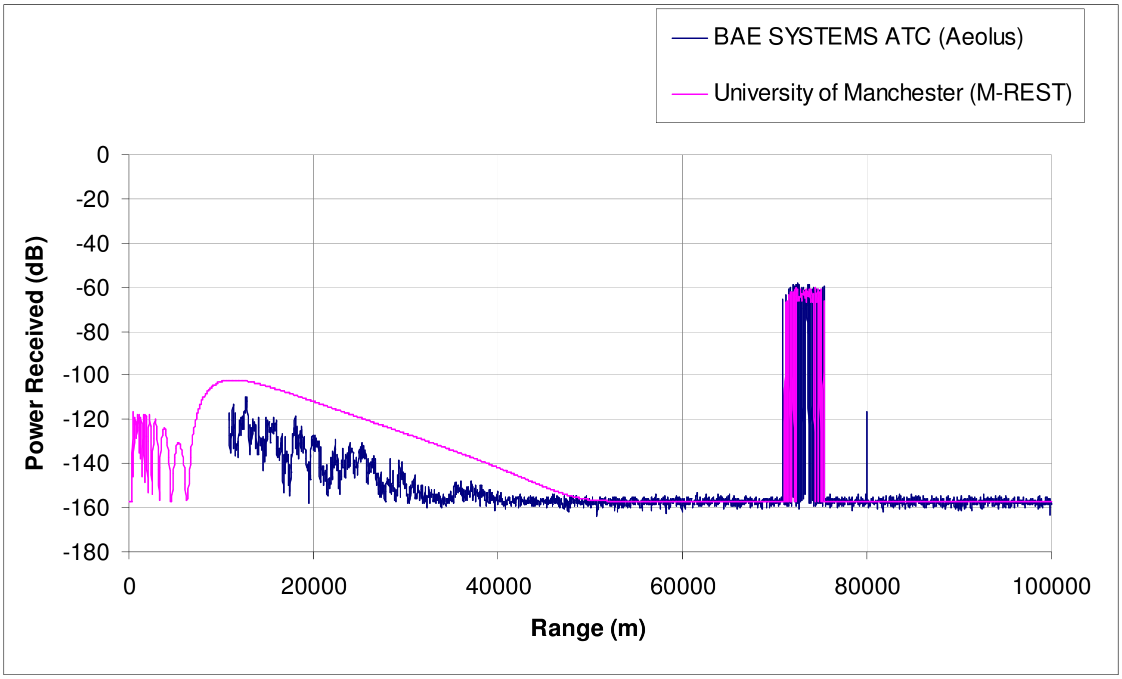

Figure 12.1: Comparison of Radar System Output

In general, the agreement between the codes was good but there were a number of differences including a difference in the noise floor of ~20dB. The clutter levels were broadly similar but in some cases the received power differed by up to 40dB.

In summary, the code-validation activities provided some confidence in the accuracy of both models. However, there were a number of differences between the outputs from the models. Further work is required in order to gain a better understanding of the sources.

13 Annexe B : Blade RAM Lightning Strike Testing

The integration of the RAM components was identified as a potential risk to the lightning strike protection of wind turbine blade. Whilst it was not possible to solve the problems associated with lightning strike, a small test panel exercise was undertaken to determine if the integration of the RAM components were likely to introduce any problems as a result of the conductivity of the RAM material being higher than that of the standard glass composite.

Flat panels were manufactured based on the RAM schemes proposed for application in the wind turbine blade leading edge, trailing edge and mid-blade region. High voltage and high current lightning strike tests were performed at the High Voltage and Direct Effects test facilities at Culham Lightning Ltd.

Figure 13.1 shows a blade leading edge test panel during high voltage testing.

Figure 13.1: Blade Leading Edge Test Panel during High Voltage Testing

All test panels survived the high voltage testing without any damage.

Figure 13.2 shows a blade mid-section (with lightning strike protection) after high current testing. Figure 13.3 shows a blade mid-section (without lightning strike protection) after high current testing

Figure 13.2: Blade Mid-section (with l/s protection) after High Current Testing

Figure 13.3: Blade Mid-section (without l/s protection) after High Current Testing

It can be seen from the figures above that the lightning strike protection scheme helped prevent a significant amount of damage within the test panels. The majority of test panels were manufactured without an integrated lighting protection scheme and so many of the panels were destroyed during the high current testing. The results indicated that a redesign of the lightning system would be necessary but the initial indication is that the mid section of the blade may not be so significantly affected.

In future it is recommended that the lightning strike testing be repeated using representative RAM panels (which include a lightning strike protection scheme in). It is also recommended that a RAM treated blade tip section be manufactured and lightning strike tested.

14 Annexe C : Marine Radar Pulse Measurements

The University of Manchester undertook marine radar output pulse measurements for use in the radar modelling impact studies. The notes below briefly describe the measurement of a standard Raymarine Model 9S 10kW radar scanner such as is widely used for navigational radar.

The measurement system was configured to enable measurements of the radar pulses to be made over a wide dynamic range by the use of a gating technique and the noise floor of the measurement system, enhanced by the use of averaging methods built into the data acquisition and processing software.

Measurements were made using this system of radar transmitter pulses at all available pulse widths, ranging from 1.2µS to 65nS. A typical result for the 1.2µS pulse width (50 average) is shown in Figure 14.1. Figure 14.2 shows a typical result for a 65nS pulse. The maximum pulse amplitude is approximately +6dBV and the average noise level is -58dBV giving a dynamic range of 64dB.

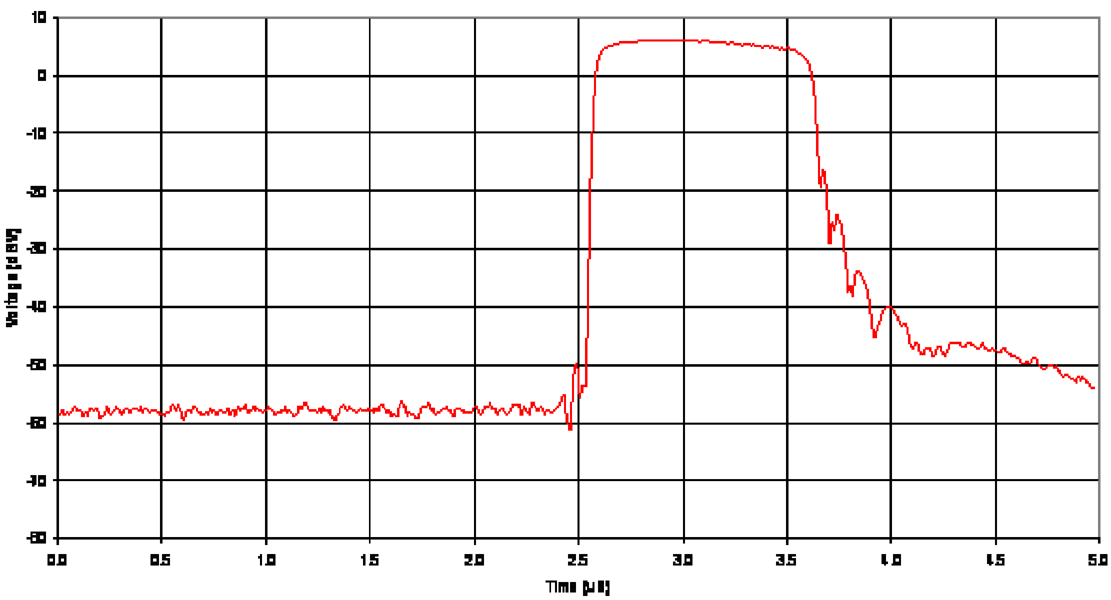

Figure 14.1: Raymarine 9S 1.2 s Output Pulse

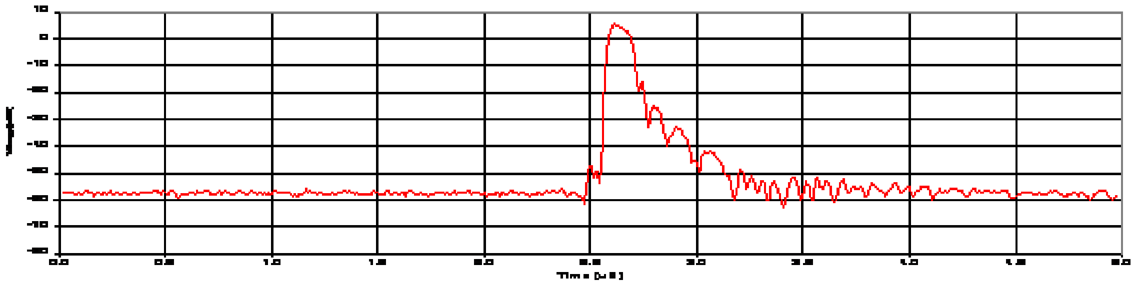

Figure 14.2: Raymarine 9S 65 s Output Pulse

The SSB noise figure of the measurement system from the mixer RF input to the output of the ungated 70 MHz LPF was measured and, for an IF of 50 MHz was 12.7dB. The measured gain between the same points was 31dB. Given the pulse amplitude displayed on the DSO, the level of the transmitter signal at the mixer input was calculated to be -15dBm. Assuming a 70 MHz noise bandwidth for the system, the theoretical noise power in a 50 system at the mixer input is -80dBm. Comparing the noise and signal levels at the mixer input, the theoretical dynamic range for the system is 65dB, which is close to the value of 64dB obtained in practice.