COWRIE – REMOTE-05-2004

Best practice guidance for the use of remote techniques for observing bird behaviour in relation to offshore wind farms

A report produced for COWRIE

(Collaborative Offshore Wind Research into the Environment)

consortium

by

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Non-technical summary

This report presents the work from a project that examined the ability and performance of remotely-operated techniques (such as radar) to observe the behaviour of birds when they are over the sea but near to the coast.

The coastal and offshore waters of the UK are very important, on a world scale, for several species of birds. Large numbers of migratory birds use the airspace above these waters and the UK has obligations to protect these under international law and agreements. The advent of an ambitious offshore wind energy programme in the UK has underlined our current lack of knowledge of the species, number and distribution of birds at sea and their possible interactions with wind farms.

As part of the required Environmental Impact Assessments (EIAs) for offshore wind farms, the extent to which birds will encounter newly constructed developments has to be estimated in advance of construction. In addition, an assessment of likely collision rates with turbines requires basic data on bird numbers, flight height and flight behaviour, including knowledge of the birds' abilities to avoid obstructions such as turbines.

The high costs and practical constraints associated with undertaking human observations makes automated remote sensing systems essential in order to gather enough data on the three-dimensional movement and volumes of birds moving through a proposed wind farm before and after construction. Nevertheless, some verification (by eye, or using acoustic equipment in conditions of darkness or poor visibility) of species and flock sizes is essential when analysing the information derived from remotely-operated equipment.

This study reviewed all potential applications of remote technologies, but specifically describes the ability of different radar systems to observe bird behaviour over the sea and the performance of the Thermal Animal Detection System (TADS) in detecting avoidance of turbines by birds and collisions between birds and turbines.

The study concluded that conventional marine ships' navigation radar provides the simplest approach to the collection of data by tracking bird movements in two (horizontal) dimensions, throughout the day and night, to provide an overview of bird flight trajectories and hence movements within a proposed wind farm area. However, visual observations are essential to identify the species of birds involved. The report recommends the use of TADS to identify species and to measure flock size during poor visibility and during darkness. Vertically mounted radar can also provide information on the height of flying birds, although birds near the sea surface cannot be easily detected by such radar when the wind is strong enough to produce large wave reflections.

More sophisticated radar systems have been developed specifically to detect and track birds and automatically record data. These offer improved detection range and performance in a wider range of weather conditions, but the cost of such devices is ten times the cost of traditional ships' navigational radar equipment.

Further improvements in the performance of radar techniques for monitoring the behaviour of birds are possible using available military technology. These include: increasing the bird detection range, improved detection of birds in rain, an increase in the ability to discriminate birds in space, identification of species, three-dimensional bird location and automated recording and statistical analysis. However, these improvements would increase the equipment cost still further.

The use of infrared imagery derived from TADS offers the best, if not the only, method of observing bird avoidance behaviours in close proximity to turbines and detecting actual collisions of birds with turbines. The method has been successfully tested in Denmark but has not so far detected any collisions during operations.

Other remote techniques are reviewed and discussed in the report, but few other methods are as useful, at present, as radar and TADS for these specific applications.

1. INTRODUCTION

1.1 Background

The prospect of offshore generation of clean renewable electricity from wind turbines placed in the sea offers potential relief from Man's energy addiction to fossil fuels and a major contribution towards attainment of national Kyoto targets for sustainable development. Such marine developments may avoid conflicts with landbirds (e.g. birds of prey Orloff & Flannery 1992, Barrios & Rodríguez 2004, although migrating landbirds may still collide with offshore turbines) and human "Not In My Back Yard" protests associated with terrestrial wind farms. Since the early 1990s marine wind farms have become a reality (Larsson 1994), and no fewer than 13 000 offshore wind turbines are currently proposed in European waters (ICES 2003). This represents Europe's most dramatic marine industrial development to date, covering a planned area of 13 000 km^2 by 2030 in German marine waters alone (BMU 2001, Garthe & Hüppop 2004).

Migratory bird species enjoy a high public profile and the protection of international and national legal instruments designed to protect shared natural resources. Hence, migrant birds figure prominently in the environmental impact assessment (EIA) process associated with all windfarm development projects, especially at sea. Despite a burgeoning literature on interactions between land-based wind turbines and birds (see reviews in Anonymous 2000, Langston & Pullan 2003), only nine offshore wind farms are currently operational in European waters. Hence, we lack concrete experiences from case studies upon which to base best-practice recommendations for the development of effective EIAs for planned future marine developments.

Nevertheless, with such rapid development and innovation in this sector, it is vital that there is some consensus on the basic objectives of the EIA process as this relates to birds. It is also important to agree recommended common standards relating to basic information requirements and data collection methodologies, to ensure inter-project comparisons and cross compliance. Finally, it is recommended that studies at a more strategic level are initiated, to gather data essential to support effective Strategic Environmental Assessment and regional site selection for future offshore wind farms.

1.2 Project context

COWRIE (COWRIE Steering Group, 22nd August 2002) recognised that the coastal and offshore waters of the UK are of global importance for several species of resident and migratory birds and the range of hazards posed to them by the construction of offshore wind farms. These hazards are many and varied, but generally fall under three broad headings:

1. Avoidance responses (e.g. birds are displaced from an ideal feeding distribution by the presence of turbines or maintenance activities associated with the turbines, or avoid flying near to them on migration)

2. Habitat modification (e.g. physical habitat loss under foundations or scour protection, or the creation of novel feeding/loafing opportunities that actively attract birds to the turbines)

3. Collision risk (i.e. the probabilities of individuals of different species being struck by turbines)

Of these, the latter is likely to be the most significant at the population level, because it elevates the normal death rate of species, and is likely to impact directly on annual changes in population size. However, this does not imply that the other effects are trivial, especially when the cumulative effects of, for example, habitat loss are considered in the light of the construction of many offshore wind farms along the length of a migratory bird species' corridor.

To support an adequate assessment of the risk presented by each hazard, and subsequently to monitor the actual effects or impacts of each hazard, environmental impact assessments (EIAs) need to predict the effect of each hazard and measure the potential effects each may have at the individual site level. These assessments are extremely time consuming to achieve through direct human observation and increasingly rely upon remote techniques to observe bird behaviour in a way which can provide robust objective data upon which to model realistic probabilities. For example, it is difficult for a human observer to physically watch and map the trajectories of migrating birds as they cross an area of open sea prior to the construction of a windfarm and make comparisons with post-construction observations to assess the barrier effect of the development. Such work requires the use of remote techniques, such as radar, to accurately plot migration trajectories prior to, and post-, construction even at considerable distances from the development site, albeit without quantification of the numbers of birds involved.

Radar is uniquely able to accurately plot bird flight altitude and trajectories pre- and (with limitations due to turbine shadow) post-construction of wind turbines. Radar can gather such data by day and night and in some conditions of poor visibility (although range and sensitivity are affected by precipitation). When associated with supplementary means of species verification, radar provides a very powerful tool to support the effective development of EIAs relating to offshore wind farms. This provides a means of generating the basis for predictions of potential collision risk, but also offers a base line against which to compare the observed behaviour of birds during the operational phase. Only in this way can the EIA process develop on the basis of accumulated experience from case studies.

A significant programme of offshore windfarm developments in shallow inshore UK waters is underway. For this reason, it is essential to obtain (i) some consensus on common standards and best practice in remote techniques for describing bird behaviour in relation to offshore wind turbines and (ii) to agree how the results from these techniques feed into the process of compiling EIAs. These requirements were the reasons that led the COWRIE consortium to issue an invitation to tender to address this suite of issues.

1.3 Project brief

Researchers are already applying remote techniques to the gathering of data to support pre- and post-construction studies of offshore wind farms in Denmark, the Netherlands, Germany and Sweden. CSL have used their avian radar laboratory at 35 locations in the UK over the last 2 years, including trials on an offshore jack-up barge (R. Walls *in litt.*). This experience, although limited, offers promise of comparable utility in the UK. For this reason, COWRIE have proposed that a desk study be undertaken to assess the present level of knowledge in this field, in combination with a workshop, drawing on international expertise. The project will specifically assess the degree of usefulness as well as the limitations (or otherwise) of different remote technologies for studying bird behaviour in relation to specific tasks associated with the development of EIAs concerned with UK offshore wind farms.

2. OBJECTIVES AND OUTLINE OF THE PROJECT

2.1 Defining the role of remote technologies

The most appropriate areas suitable for the application of remote technologies to collect data for the EIA process associated with offshore wind farms would seem to be in the following:

a) to provide a broad pre-construction phase description of the movements of birds (both locally feeding birds, as well as those making diurnal movements, short-distant and long-distance migrations) within a study area and compare this to post-construction scenarios. The study area should be large enough to encompass the area where effects are likely to occur as a result of windfarm construction, as well as a comparable undisturbed adjacent reference area

b) to provide parameterisation of models to estimate the probabilities of bird avoidance of rotor-blades, wind turbines and wind farms and to compare base-line observations with those post-construction

c) to provide validation of these probabilities by measuring actual collision rates associated with individual turbines

In the case of a) such a process of data gathering offers the opportunity to compare and contrast data from parts of the study area for the purposes of (i) risk assessment and (ii) as a base line for post construction comparisons. In the case of b), the overall objective will be to offer advice on best practice to assess whether flying birds (be they migrating or merely undertaking local movements) avoid wind farms altogether, avoid flying near turbines or avoid flying near rotating rotors. This modelling approach is essential in order to construct a hierarchy of probabilities that enable the observer to estimate the likelihood that any given individual bird will collide with the turbine in the course of a given time span under a range of circumstances. The actual probability that a bird crosses the sweep area of the rotors can be constructed on the multiple probability of occurrence observed under a range of different environmental conditions, including season, time of day, weather, visibility, sea state, tide conditions, etc.. In addition, the probabilities that a bird will actually hit the turbine will depend upon species, flight behaviour, flight speed, ability to manoeuvre, last minute avoidance responses, etc. Hence, the remote techniques need to be able to record multiple observations using identical data collection protocols in order to assign probabilities under a range of parameters relating to prevailing environmental conditions and the birds involved. This then offers the basis for construction of probabilities and an assessment of the range of variation under observed circumstances. Finally, in the case of c), the overall object will be to offer best practice to measure, as far as possible, the actual collision rate of birds hitting the turbine superstructure, or being mortally wounded in the vortices encountered in the wake of the turbines. As a supplement to this, it is also important to know that if, under certain meteorological circumstances, collision risk is unacceptably high, stopping the turbine blades revolving offers an effective mitigation to reduce avian collision mortality.

All the current remote techniques suffer limitations to their ability to fulfil the ideal objectives set for the tasks. Hence, the project (both the desk study reported here and the results from the workshop) will inevitably review the strengths and weaknesses, limitations and constraints associated with each of the different potential methods. The overall aim will not be to provide a recipe book approach to the use of remote technologies, but rather guide on best practice under the prevailing circumstances. In situations where complementary technologies, or other options exist to circumvent or compensate for the limitations of a specific approach, as far as possible, these will also be recommended, either during the data collection, data collation or data interpretation phases.

It is essential to establish from the start of this exercise that the results of this process reported here will be of a highly provisional nature. In Europe, and soon elsewhere, more offshore wind turbines are being constructed and more experience being gained, both in terms of the developing technologies available to monitor the effects of these structures on birds and in terms of the wealth of data obtained from additional case studies. At the moment our knowledge is very rudimentary and our experience highly restricted. For this reason, we consider that a static written document represents an inappropriate means of presenting the synthesised information arising from the project. Rather, we look to the development of a future web resource, which provides a dynamic platform upon which to provide a sequentially updated (preferably annual) source of information for practitioners.

2.2 Objectives of the project

The overall aims of the project are to provide:

1) An objective assessment of the utility of remote technologies for the specific study of bird/wind turbine and bird/windfarm interactions and specifically their ability to meet objectives set for their use

2) Guidance on current best practice of the most suitable technologies, and

3) Recommendations for further methodological development to increase utility.

The programme will deliver a guidance document/manual offering guidelines on the best practice applications of different tools and approaches based on existing experience for those involved in the offshore wind energy industry and elsewhere (especially the ornithological research community). Harmonisation in the development of methods and data collection is essential if we are to derive maximum benefit from shared experiences in the future to best predict the effects of offshore windfarm developments. The final report will offer guidance based on a review of experiences from existing methodologies (both from the grey and published literature, but also drawing on extensive internal experiences available within NERI, her partners and other experts), as well as offering likely profitable future possibilities for methodological development. The recommendations will aim to be statistically robust and consider the range of variables influencing the use of different methods. The guidelines will explore the strengths and weaknesses of a range of recorded parameters associated with each method, the circumstances under which different approaches would be recommended and will recommend general standard sampling procedures, data collation, storage and analysis for the methods recommended. The document will then naturally offer a standardised protocol for gathering data on offshore bird behaviour using remote technologies. Hopefully, this can be adopted for use at any offshore wind farms around the UK, using agreed common standards and optimal methodologies, which will greatly improve comparability of data from different future studies.

2.3 Project team

The project team combined NERI's extensive field-tested experience in the application of remote technologies to ornithological problems in hostile offshore conditions with QinetiQ's cutting edge technical expertise in the development and use of new (especially radar) technologies.

NERI has been involved in the studies and EIAs associated with all five proposed (and both existing) offshore wind farms in Denmark. These projects have necessitated rapid research and development into the use of remote techniques to optimise data collection in challenging marine environments, but see:

http://www2.dmu.dk/1_Om_DMU/2_afdelinger/3_vibi/publikationer1_en.asp for the recent reports of these activities. The work of the department has also involved provision of advice to offshore windfarm developments in many other European states based on these experiences, which in turn has contributed to the extended international experience of the group. The work has been co-ordinated by Mark Desholm, currently a Ph.D. student in the Department of Wildlife Ecology and Biodiversity, supported by Johnny Kahlert, Research Biologist and Tony Fox, Research Professor. All have had experience with the application of remote technologies in supporting the development of offshore windfarm EIAs.

The technical input relating to radar technologies and the potential these offer has been provided by Patrick Beasley of QinetiQ, Europe's largest independent research organisation, employing more than 250 people working on all aspects of radar ranging from hardware design through to radar data analysis. Their Radio Frequency Sensor Technologies group specialises in research and development of high resolution, state-of-the-art, solid state radars including dedicated bird detection radar for EIAs and bird warning at airports.

2.4 Desk study and literature review

The approach taken to address the needs of the project was set out in the tender document. However, the first major objective has been to complete an extensive literature and present an "access to tools" resource, listing, categorising and reviewing the extent and scope of the existing literature relating to existing experiences, techniques and potential applications. This has covered both the internationally refereed scientific literature and the more inaccessible grey literature that currently contributes most to this field.

On the basis of this extensive desk study, a provisional document was drawn up for circulation and consultation to various interested parties and experts around the world. The document was mounted on the COWRIE web page on 21 March 2005 at the following address:

http://www.thecrownestate.co.uk/1355_remote_techniques_int_rpt_05_03_21.pdf

The results of this consultation process and the feedback received during presentations and discussions from a specially convened workshop, held at the QinetiQ site on the Malvern Technology Centre, Great Malvern, Worcestershire during 4-6 April 2005, have now been incorporated into this revised report.

2.5 Defining the problem

As described above, this report addresses and identifies the specific needs for remote data gathering methodologies necessary to support the EIA process for offshore wind farms in the UK. The necessary data components for an effective EIA will be defined below, which then define the precise data requirements. These ideal objectives shape the approach that is needed and the review of the literature and unpublished experiences will enable an assessment of the effectiveness of different methods and their application in the past. The synthesis of these experiences will enable an assessment of the relative strengths and weaknesses of different techniques in achieving set goals and establish the constraints (e.g. practical, logistic or cost considerations) which act upon their attainment. Based on a comparison of the experiences, it will be possible to offer a suite of recommendations for best practice under a range of prevailing conditions and expectations.

Although the invitation to tender documents outlined two major areas for special attention (namely Radar and Thermal Animal Detection Systems), the proposed literature survey and review will cover all other potential remote methodologies as follows.

2.6 Radar

Radar is one of the more powerful tools available to describe the movement of birds in three-dimensional space and its use has been long-established and well described (e.g. Lack & Varley 1945, Eastward 1967, Bruderer 1997a, 1997b, Gauthereaux & Belser 2003). Conventional radars use short high-power pulses of radio waves and detect the "echoes" of weaker reflected signals that return from objects. Hence, it can be used in darkness as well as daylight, overcoming many of the limitations associated with visual observations. It would appear that the transmitted electromagnetic pulses have no effect on migrating birds in contrast to those associated with the use of strong light sources (Bruderer et al. 1999). Weather radar equipment (e.g. Koistinen 2000) and ordinary conventional marine navigation radar (e.g. Harmata et al. 2003) can be used to great effect to track bird movements because of the significant reflectivity from flying birds, which has already been exploited for windfarm EIA studies. At the most basic level, data gathered using such technologies is vital to characterise the volume of bird movements that occurs within a proposed windfarm site prior to (e.g. Cooper 1996, Gauthreaux 1996) and after its construction (e.g. Johnson et al. 2002, Kahlert et al 2002). Normal horizontally mounted marine navigation radar offers the ability to accurately map the trajectories of flying birds or flocks of birds in time and space (e.g. Desholm 2003a). Vertically mounted scanning radar can supplement by measuring the specific height at which birds are flying. The use of more sophisticated tracking radar can lock on to individual birds (Alerstam & Gudmundsson 1999), combining measurements of their movements in three-dimensional space (i.e. including flight altitudes) with a limited ability to determine species. Although radar cannot identify species, tracks can be assigned to taxa on the basis of flight speed (e.g. Larkin & Thompson 1980, Larkin 1991, Evans & Drickamer 1994, Bruderer & Boldt 2001) or wing beat frequency (e.g. Renevey 1981, F. Liechti, pers. comm.). However, the pencil thin beam of a tracking radar limits its ability to track large numbers of flying objects simultaneously, and has other practical limitations (see discussion below). Nevertheless, based on such measurements, it also becomes possible to model the level of bird movements occurring not merely within the windfarm (e.g. Kahlert et al. 2002), but specifically those that occur within the sweep height of the turbine blades. Given such detailed information, it becomes possible to model predicted levels of collision rate under a range of different environmental conditions for different species. Radar is also useful for providing detailed information on behavioural responses to wind farms, flight trajectories and species-specific avoidance under a range of environmental conditions, which again can be used to build into models to predict collision risk probabilities.

Despite the advantages of radar, the use of such techniques does have limitations. For example, radar gathers spatially accurate data on the paths taken by flying birds well beyond the range of the human eye. Hence, supplementary information is required (using techniques such as visual or thermal observations, detection of birdcalls, complementary remote systems or other methods) to confirm the specific species involved, which are creating the traces recorded on the radar screen. Furthermore, radar functionality may deteriorate in conditions of poor visibility, notably high atmospheric moisture levels, and suffer from the shadow effects of the turbines post development. Storm-driven movements of birds could potentially increase the risk of collision, but the reduced performance of conventional surveillance radars (especially the X-band radars) in stormy weather has to be taken in to account. Different radar approaches (S-band, X-band, tracking radar, etc.) have different advantages and limitations with respect to operating accuracy, range and range resolution, weather conditions, suitability of platform, problems with clutter reflection from wave tops, cost-effectiveness etc. These limitations are compared and contrasted in the review to underline the suitability or otherwise of different methods and equipment for specific applications.

This analysis attempts to highlight the shortcomings of existing equipment and, where possible, recommends modifications or upgrades to improve performance. QinetiQ have also produced a ‘desired’ specification for a bird detection radar for EIAs based on the status of existing, and near-future radar technology including recommendations on the method of data capture and analysis.

Based on extensive literature survey, product testing and first-hand experience of NERI, QinetiQ and many other users, the review offers a suite of best practice recommendations for the use of radar equipment and approaches for a range of applications.

2.7 Thermal Animal Detection Systems TADS

NERI originally developed the TADS technology as a means of gathering highly specific information about actual collision rates, flight behaviour and avoidance of birds in the close proximity of turbine blades. The major motivation for its development has been as a means of generating data in a way that is more effective than can be achieved by human observation alone, especially in offshore environments under difficult weather conditions. Given an adequate power supply and optic-fibre cabling links to the shore, the monitoring of turbines using this system can be controlled remotely (at a distance of many kilometres) via a computer link, with no necessity for the on-site presence of an operator.

The implementation of the TADS system has been pioneered by the Department of Wildlife Ecology and Biodiversity at NERI (Desholm 2003b, Desholm 2005), which basically uses infrared video camera equipment to capture images of the passage of birds through a particular scene. The system is triggered by the movement of a warm body (such as that of a bird) within a defined field, avoiding the need for human viewing of endless blank video recordings. Objects within a predetermined thermal range and size can be defined to further limit the capture of spurious thermal images not containing birds. Provisional assessments indicate that reasonable species distinction can be achieved by a combination of size, shape, flight behaviour and wing beat frequency. The successful deployment of such a method offers the possibility that these cameras can remotely capture imagery relating to:

(i) collisions with a turbine,
(ii) specific avoidance behaviour of species in close proximity to the turbine blades,
(iii) birds that pass through the turbine blade sweep area only to be injured in the associated turbulence vortices and
(iv) night time species composition, flock sizes (feature unique to TADS) and flight altitudes

Although TADS have the potential to provide more robust information about bird behaviour in close proximity to turbines than any other system, they too have their limitations. The field of view is very limited and the distance over which individual small birds can be detected and identified is relatively short, restricting the potentially monitored area of airspace considerably. The functionality of TADS may deteriorate under conditions of high humidity, although the system can still provide considerable information beyond the range of the human eye and other similar remote techniques.

2.8 Other remote techniques

The review also assesses the possibilities and potential of other (some as yet undeveloped) techniques for collecting information on bird flight and behaviour both pre- and post-construction of the offshore wind farms. These include the use of ordinary video surveillance equipment, sound systems, strain gauges, pressure sensors, etc.

3. REVIEW OF EXISTING TECHNIQUES

3.1 Radar

Radar ornithology has been a well-established research field for several decades (Nisbet 1963, Eastwood 1967, Konrad et al. 1968) and several reviews have been published on this topic (Vaughn 1985, Bruderer 1997a, Bruderer 1997b, Gauthreaux & Belser 2003). The relevance of using radar techniques when dealing with flying birds and offshore wind power production is obvious. Whether data are being gathered to compare pre- versus post-construction flight trajectories to assess the barrier effect or to assess collision risk, radar offers a unique remote sensing tool for describing bird movement in three-dimensional space. Specifically, the mapping of flight trajectories within and around offshore wind farms enables the researcher to assess the effect of establishing such man-made obstacles in the open sea. The results of radar studies may also help to establish some of the mechanisms determining perception of risk and level of avoidance response shown by different bird species towards offshore turbines.

In this section, we briefly examine the available hardware options and their suitability for the task in hand. As a background to this discussion, it should be remembered that the use of any equipment using radio frequencies requires licensing and guidance on this subject is provided in Appendix 9.1.

3.1.1 Available hardware

The various commercially available types of radar can be classified in different ways. First of all, the radar operating frequency can be subdivided into frequency bands, with the most frequently used radars in ornithological studies being the X-band (3cm; 8-10.8GHz), S-band (10cm; 2.3-3.7GHz) and L-band (23cm; 1.2-1.4GHz). Secondly, the peak power output differs with regard to the strength of the radar signal (ranging between 10kW and 200kW), which determines the operational range for a given target size. Finally, referring to radar equipment after its mode of operation is widespread throughout the literature, most commonly grouped between a) Surveillance radar, b) Doppler radar, and c) Tracking radar as discussed below.

Surveillance radar systems

These radars are most often used for surveillance of large moving objects. These are most commonly associated with detection of ships (know as Marine navigation radar), aircraft (known as Airport surveillance radar (ASR)) or clouds/precipitation (Meteorological radar or Weather radar). All are characterised by a technique for scanning a beam constrained in its azimuth beam width. Conventional radars use a mechanically scanning antenna, which typically is either shaped as a “T-bar”, or as a parabolic dish (which provides a conical or pencil beam). More sophisticated radars use phased arrays which can scan the beam electronically without the need for rotating parts but these are expensive and, almost exclusively, confined to military applications.

Surveillance radars can be used to map the trajectories of the moving target and the echo trail feature makes each echo visible for a given amount of time. A Moving Target Indicator (MTI) represents built-in software that excludes stationary and slow moving targets from the monitor (in radar terms, Plan Position Indicator, or PPI). Area MTI, which is available on some marine navigation radars, is a relatively crude technique which subtracts the static picture from new data. It is known as a non-coherent technique which means that only the amplitude of the signal is available, phase information is not available. The technique is good at removing the visual distraction of returns from large static targets on a PPI. However, it is ineffective in tracking small targets against a strong target background as produced by radar returns from ground, sea or rain. In fact, it can effectively desensitise the radar and is not recommended for gathering a calibrated record of bird movements.

Coherent MTI, which is implemented in military radar and for the high end of the professional market, uses phase information to separate moving targets from static targets based on Doppler characteristics. A small moving target such as a bird, which may be one thousandth's the radar size of the background against which it is flying, can be readily detected. Coherent radar, until relatively recently, has implied high manufacturing cost because of the need to produce a very stable transmitter source. Solid-state radar techniques now provide the means to implement coherency at significantly reduced cost.

Conventional marine navigation radars are predominantly magnetron-based, a technology which dates from the 1960s and are 'non-coherent'. As such, they offer no scope for eliminating the masking of bird targets by reflections from rain. Post-collection analysis of radar data recorded using marine navigation radars has also in the past been very basic. However, dedicated bird detection radar (e.g. the avian labs) allows more sophisticated analysis using spatial modelling techniques in a GIS platform such as those developed by CSL over the last two years.

Low-powered surveillance radars can detect individual birds within a range of 0.5 to 3 kilometres and flocks of birds to 10 kilometres (see Appendix 9.2). However, the detectability of a bird varies enormously with the bird's reflective properties, which are mainly linked to physical size (Appendix 9.3) and atmospheric conditions (Appendix 9.4). These radars can be mounted either on a tripod, an aircraft, boat, jack-up barge or vehicle.

High-powered surveillance radars can detect birds within a range of 100-240km (Gauthreaux & Belser 2003) and have been applied using stationary air route surveillance radars (ARSR), airport surveillance radars (ASR), weather surveillance radars (WSR) and military surveillance radars (MSR). Some of the high-power L-band radars are also equipped with a Moving Target Indicator (MTI) that prevents stationary or slow moving echoes from being displayed at the monitor. These radars are ideal for determining bird migratory routes over very long distances but, because their range resolution is very coarse, they are inappropriate for the detailed monitoring required for EIAs for offshore wind farms. Also, they tend to be physically very large and are fixed in location.

Fixed-beam radar systems consist of the same hardware as the surveillance radar systems, but in contrast use parabolic dishes to reduce the elevation beam width and to increase radar detection range. As the name indicates, these systems use a fixed beam collecting data in a predefined line of interest. Often these systems are modified marine navigation radars where the "T-bar" antenna has been substituted with a fixed parabolic dish. Whilst increasing detection range, the disadvantage of narrowing beam widths is that spatial coverage is reduced and, hence, the ability to obtain statistical data over a wide area is reduced.

Doppler and pulse Doppler radar systems

These systems are used in a diverse variety of applications like WSR's or small portable low-powered traffic speed control Doppler radars (Evans & Drickamer 1994). The characteristic of these systems is their ability to detect the Doppler frequency shift due to the target's radial component of velocity and hence distinguish them from the static background. They use these data to gather information on the velocity of the target and, potentially, can provide information on wing beat signature if the bird remains within the radar's beam for sufficient time to extract data during the course of a full wing beat cycle.

The new-generation of weather Doppler-radar (WSR-88D) used for weather forecast throughout the US (154 individual radars) produce pictures showing the base-reflectivity (density of targets), base-velocity (radial velocity), and vertical wind profile (movement of small particles). The WSR-88D operates in the S-band with a peak power output of 750kW and a scanning pencil beam from a big parabolic disc (with a diameter of c. 9m). The radar uses bursts of RF energy and so, by timing the returned target signals can measure range as well as velocity by measurement of Doppler shift. The minimum pulse width is 1.57μs corresponding to an inherent range resolution of 230m. Radar techniques (pulse compression) are being applied to improve the resolution to 50m. The main drawbacks to trying to use such a system for offshore EIAs are its cost (several £M), its size, its inability to detect single birds and the fact that the UK does not currently have such a capable system.

Tracking radar systems

These systems were originally made for military purposes and usually are designed to track a single target at a time. State-of-the-art military phased array systems are capable of simultaneously tracking multiple targets but cost many millions of pounds. Tracking radars often have a high peak power output to obtain very good target range and have a relatively large antenna. The radar beam is of the narrow pencil type and operates often in X-band and Ku-band. Most often the air space has to be scanned manually by the operator for locking the radar onto the target, but a pre-programmed automatic scanning for targets can also be applied whereby after the radar locks onto the target, it can be programmed to follow it. The returned signal can be used to describe the three-dimensional movements of the target and provide data on ground speed, heading and modulations of reflectivity. Tracking radars are therefore also capable of analysing wing beat signatures, which requires that the radar is focussed upon an individual bird for at least the period of one full wing beat. This necessitates use of a tracking radar or very slow scanning radar. As mentioned earlier, the coherency of the radar is critical in determining radar performance. An incoherent tracking radar can measure the amplitude fluctuation of radar returns and can thus measure the wing beat characteristics of a single bird. However, if a flock of birds is illuminated with an incoherent radar, the amplitude fluctuation of the individual birds will destroy the echo signature for potential wing beat frequency analysis. A coherent tracking radar can measure the Doppler spectra of individual birds and, in principle, can still provide useful wing beat information for a flock of birds. This is a new measurement technique for bird signature analysis which, as far as the authors are aware, has not been practically implemented.

Avian radar studies in a windfarm context

So far only X-band and S-band surveillance radars have been used in ornithological research in relation to wind power production facilities. Surveillance radars are produced for scanning 360° of azimuth to monitor moving targets. However, in order to collect data on the flight altitude supplementary radars with vertical scanning modes have been applied as well as modified systems where the scanning "T-bar" antenna have been substituted with a fixed parabolic dish.

In Denmark to date, four studies have been conducted using marine navigation radars. Tulp et al. (1999) used a 10kW X-band marine navigation radar (Furuno FR811) to study the avoidance behaviour of wintering Common Eiders *Somateria mollissima* to an offshore windfarm of ten turbines. In this study, a marked evasive effect was noted up to a distance of 1,500 metres from the turbines, with a reduced flight activity in the vicinity of the park.

Pedersen & Poulsen (1991) used a 10kW (Furuno FR-1500) surveillance radar with a scanning "T-bar" antenna for studying the migration paths at an inland wind turbine. They documented that the birds changed direction by 1-30 degrees when passing the turbine, irrespective of whether the turbine was in operation or not.

At the Nysted offshore windfarm (Desholm et al. 2003, Kahlert et al. 2000, 2002, 2004) a BACI-designed study is running and here a 25kW Furuno marine navigation radar has been used. This radar study mainly concentrates upon movements of migrating birds, especially the migrating waterbirds which are the subject of intensive study. Due to the relatively long distance (5 km) between the tower on which the radar was mounted and the windfarm area, it turned out to be rather difficult to map the migration trajectories of the landbirds whereas the larger bodied water birds were easier to track. Profound avoidance behaviours have been recorded in a relatively large proportion of the water birds avoiding the windfarm as a whole, and of those entering the windfarm showing high tendency to fly in the corridors in between the individual turbines (Desholm & Kahlert 2005). This is the same study as TADS was developed for and is still used.

At the Horns Reef offshore windfarm in the North Sea (also in Denmark) the same Furuno FR2125 radar as described for the Nysted-study has been used (Christensen et al. 2004). In the same study, a Furuno 10kW marine navigation radar has also been used. The difference in peak power output resulted in a marked difference in performance with the 25kW radar detecting flocks of birds much more easily and at longer ranges than the smaller 10kW radar. In this study, avoidance behaviours of wintering and moulting Common Scoters *Melanitta nigra* as well as amongst migrating water birds have been observed.

In the UK, the Central Science Laboratories have accumulated considerable experience with radar in support of measuring bird strike risk associated with airports over the last two years. They have used S-band Furuno 2135 and X-band 2125 bird detection radar with some success. Recent projects have included monitoring of offshore bird movements in the Greater Wash area, eastern England, goose roost flight movements on Kintyre in Scotland and inland movements of waterbirds between different lakes in a large gravel pit complex (Cotswold Water Park). To date they have operated at 35 locations on 112 days and the equipment has generally performed well, tracking up to 3000 movements per hour. Azimuth scanning could detect individual passerines (starlings *Sturnus vulgaris*) out to 3 km and flocks of thrushes (*Turdus* spp.) out to 11 km (species identification being confirmed using complementary visual tracking), vertical tracking could provide 2 km range, but sea clutter hampers interpretation of signals low over the water surface. The effectiveness of the system is hampered by data complexity, but automated data capture and storage to a GIS ensures standard quality data collection. To date, no adjustment has been made for ground/air speed but this would be feasible. Performance is reduced in rain, but with S and X-band radar, geese could still be detected out to 8 km range in light drizzle. The equipment cost some £150,000-200,000 for the radar and a similar amount again to develop appropriate software systems to gather data. CSL are currently planning to issue an invitation to tender for a new bird detection radar system. The requirement is for a fully mobile system capable of deployment on stable offshore platforms and of detecting birds out to 20 miles. The system should also be capable of measuring the altitude of birds to 1.5 miles and must be able to automatically discriminate between birds and background clutter.

Recently, a radar study in the Dutch part of the North Sea has been initiated (Sjoerd Dirksen in litt.). In 2003, Bureau Waardenburg contracted DeTect Inc. (www.detect-inc.com, Florida, USA) to install a custom-engineered environmental radar system ‘Merlin’ on Meetpost Noordwijk, a government owned research platform, situated 10 km off the Netherlands shoreline. The project was established as a baseline study for the impact assessment for the Dutch Near Shore Windfarm (NSW). NSW is a 36 turbine windfarm to be erected 12-18 km off the Dutch coast at Egmond. ‘Merlin’ consists of a vertically operated X-band and a horizontally operated S-band radar, connected to computers running algorithms on the raw radar data. The system allows for automatic registration of signals of flying birds to be entered directly into a database. Simultaneous measurements by radar and by field observers provide a detailed picture of species and flight patterns. Results of the fieldwork (Oct 2003 – Nov 2004) are due to be published in summer 2005.

In the US, a similar type of system (MARS) has been applied in the environmental impact assessment of the proposed Cape Cod windfarm in the Nantucket Sound. (Geo-Marine Inc. 2004). The MARS system was deployed both on a cliff top at Cape Poge, 8.5m above mean sea level (AMSL) and on a jack-up lift boat in Nantucket Sound at 4.6m AMSL. It consisted of a 30kW conventional S-band marine navigation radar (TracScan) together with a vertical scanning 25kW X-band marine navigation radar (VerCat). The antenna of TracScan was shimmed to improve elevation coverage and to improve performance against reflections from the sea. VerCat was operated typically to 0.75 nm down range and 1.5 nm in altitude whilst TracScan operated typically to 4 nm. It was not possible to reliably correlate data from the two radars so the results were derived separately. Using these off-the-shelf radars it was not practical to determine objects to species, although they could be assigned to a broad class of bird size (small <80g, medium 80-800g, and large >800g) on the basis of radar echo and bird mass. This limitation was further compounded by the difficulty in resolving the number of birds because of the coarse range and angular resolution of the TracScan radar. The report also commented that the X-band radar was particularly sensitive to rain which can appear similar to bird detections and makes automatic detection of birds in rain unreliable.

As an aside to the technical performance of the MARS system described above, the EIA carried out for the Cape Cod windfarm has received criticism from Massachusetts Audubon Society who carried out a detailed technical review of the avian sections of the EIA. The main criticisms were;

1. Poor discrimination between targets such as bats and terns
2. No targets were recorded below the radar heights which is inconsistent with visual observation
3. Additional analysis required to focus on greater discrimination of targets by flight speed and target density
4. A variance between the EIA's estimated annual collision mortalities (364 birds per year) and Mass Audubon's own estimate (2,300 to 6,600 birds per year).

These comments are not necessarily a criticism of the radar's used, more about the way that the data has been analysed. As a result a further two-year radar study has been ordered at an estimated additional cost of $320,000.

A similar radar setup has been used for studying the fall migration over the vicinity of the Chautauqua study area, a proposed windfarm site. The land-based mobile laboratory consisted of a single 12kW X-band marine navigation radar that could be mounted either horizontally or vertically. As above, the antenna of the horizontal scanning radar was altered to minimise unwanted reflections. With this setup individual hawks were detectable to 2-3 km, single, small passerines to 1-2km and flocks of waterfowl to 5-6km. Again, detection in rain was limited due to backscatter from rain clutter. Also, false detections were produced by large groups of insects.

In the German part of the North Sea and Baltic Sea several governmental studies have been conducted in recent years. Some of these have applied radar for data collection, and at the ongoing study at the offshore platform "FINO I" migrating birds have been studied using two surveillance radars (12kW and 25kW; Dieter Todeskino pers. comm.). Guidelines exist for conducting EIAs at proposed offshore wind farms, recommending a monitoring scheme of 100 days and nights over a two year period (mostly from ships), using both vertical (1.5 nm range) and horizontal radars (3 nm range; Dieter Todeskino pers. comm.).

Tracking radars have so far not been used in a windfarm context. To some extent, this can be explained by the way this system locks on to target objects. Locking a tracking radar on to a migrating bird/flock approaching a windfarm would provide a good trace of the movement, until such time as the bird(s) passed in front of a moving turbine. The result would be that the radar locks on to the first turbine passed by the bird, since the rotating blades reflect a much stronger pulse of energy than small flying birds. Thus, the risk of adopting such an approach is that only the approach part of the flight trajectory would be mapped, leaving the researcher with no information on the flight pattern of birds in the immediate vicinity of the windfarm – precisely the objective of the study.

Avian radar studies in non-windfarm contexts

A extensive literature exists on the topic of radar ornithology, starting in the mid forties with the work of Lack & Varley (1945) and proceeding over the next two decades with the work by Graber & Hassler 1962, Nisbet (1963), Eastwood (1967), and Konrad et al. (1968). During the last 30 years, the vast majority of radar studies on birds have been performed on migrants mostly in North America, Europe and Israel.

In North America, the vast majority of studies have been carried out using smaller surveillance radars and the more powerful and long-range weather radars. Firstly, the WSR-57 and ARS-7 have been used for studying the volume and heading of avian migrants over most of the US (Gauthreaux 1970, 1971, 1991). About ten years ago, all the old WSRs were replaced with a new generation of radars (NEXRAD; WSR-88D) applying the Doppler methodology which has proven very efficient in collecting data on migrants on a more strategic and larger scale (Gauthreaux & Belser 1998, Russel & Gauthreaux 1998, Diehl et al. 2003, Farnsworth et al. 2004). The field of radar ornithology in North America has also developed using smaller low-powered surveillance radars for more local registration or studies of bird movements. Some of these studies have been using standard marine navigation X-band radars for example to trigger acoustic bird alarm calls, pyrotechnics and bird tear gas to automatically scare birds away from contaminated power plant pools (Stevens et al. 2000) or to compare counts of Marbled Murrelet *Brachyramphus marmoratus* by combined radar and audio-visual technique (Cooper & Blaha 2002). The great variety in different study objects and study areas limit the usefulness of standard marine navigation radar applications, and hence, many studies have modified their equipment to a greater or lesser degree. Some radar studies at in-land locations have applied different anti-ground clutter arrangements, like a ground clutter reduction screen (Cooper et al. 1991) or by simply tilting the “T-bar” antenna upwards 12.5° above horizontal (Williams et al. 2001). Others have replaced the slotted wave-guide antenna with a more or less vertical parabolic disc for measuring the flight altitude of birds (Cooper et al. 1991, Cooper & Ritchie 1995) or simply tilted the scanning “T-bar” antenna in to a vertical operation mode (Harmata et al. 1999).

In Europe, radar ornithology has been dominated by the tracking radar work performed by two different research groups. The first group is based at Lund University in Sweden and has centred upon the work undertaken by researchers using long-range military tracking radars, dealing mainly with migration and orientation of free flying birds. They have used one stationary tracking radar mounted on the roof of the University to study geese, waders and swifts (Green & Alerstam 2000, Bäckman & Alerstam 2001) and a mobile tracking radar placed on the deck of an ice-breaker on expeditions to the Arctic region pioneering the field of Arctic radar ornithology (Gudmundsson et al. 2002, Hedenström et al. 2002). Wing beat frequencies have been derived from data on modulations of reflectivity and in this way indications of the likely species under study have been assessed. In the seventies the same research group used high-power L-band military radars to study water bird migration in the southern part of Sweden (Alerstam et al. 1974).

The second major research group has been centred around the work by the Swiss Ornithological Institute using the so-called “Superfledermaus” system, an ex-military fire-control X-band 3.3 cm 150 kW tracking radar mounted on a truck, dating from 1969. This radar system uses a fixed beam to track single targets, as well as undertaking continuous fixed beam sampling. This radar system provides wing-beat patterns of individual birds (but not flocks) but generates large amounts of data (70 Mb in 14 seconds) which creates problems of storage. This has been used to great effect at a variety of locations in the Northern Hemisphere, including Israel (Bruderer 1994, Bruderer et al. 1995, Bruderer et al. 1999, Zehnder et al. 2002). The effect of light beams (Bruderer et al. 1999) and extent of reverse migration (Zehnder et al. 2002) in avian migrants have been amongst some of the topics tackled using the “Superfledermaus”.

In Denmark, high-power L-band radars were used in the first radar study in the country, aiming at minimising the collisions between aircraft and birds (bird-strikes; Rabøl et al. 1970). In Finland, Koistinen (2000) has published an analysis of the influence of migrating birds on the ability to perform real time wind monitoring using weather radars, and hence, it is has been possible to apply an automatic diagnosis system to eliminate spurious atmospheric wind records attributable to flying birds.

In the Netherlands, the group of Luit Buurma (Royal Netherlands Airforce) has been studying migrating birds using the Flycatcher radar as well as the Robin radar system (Buurma 1995). The main objectives of these studies have been to warn pilots about high avian migration volumes to reduce the risk of bird strikes.

Pros and cons of different hardware

From the outset, it is very important to stress here that none of the radar applications described above can be used to detect collisions directly. Hence, in the current discussion the application of radar is confined to describing bird movements in three-dimensional space. Even in this respect, the different radar types differ in their ability to meet the specific needs of the brief developed here (see Table 3.1.1). The surveillance radar cannot distinguish between echoes arising from single individual and flocks of birds (Table 3.1.1). Most often the echoes will represent a flock of birds, and hence, if some of these birds collide with the turbine the moving echo on the radar monitor will continue on the other side of the turbine as if nothing happened.

Table 3.1.1. Specifications of the major different types of radars, with an appraisal of their strengths and weaknesses. None of the specified radar types can be used to measure either collisions directly or flock size. * In Germany four different software solutions are available (Biola, IfAÔ, IfV, IBL).

Parameter	Marine navigation radar	Pulsed Doppler radar	Avian Laboratory radar	Tracking radar
Bird detection range	0.5-12km	1-200km	0.5-12 km S-band (horizontal) 1.4 km X-band (vertical)	1-130km
Ability to measure flight altitude	Yes (vertical beam or "T-bar" antenna)	Yes (distance dependent density differences)	Yes (using X-band radar)	Yes
Map trajectories (avoidance behaviour)	Yes (by hand on a transparency or by use of special software*)	No	Yes by automated data-logging of radar data to network of PCs. All analysis in ArcMap GIS.	Yes
Flight speed	Yes	Yes (radial velocity)	Yes as a field in real-time generated database	Yes
Heading	Yes	Yes (based on Doppler shift)	Yes as a field in real-time generated database	Yes
Wing beat frequency (identification)	No	No	No	Yes
Physical dimensions	Small and light	Large and heavy	Large in trailer configuration, but radar antenna head demountable	Large and heavy
Mounting requirements	On land: tripod/ car Off shore: tower/jack-up barges/large ship (>40m)	Stationary	On land: truck, trailer Off shore: tower/jack-up barges/large ship (>40m)	Stationary or in small truck
Hardware costs	Low (£15,000-20,000)	High	£150,000	High (>£150,000)
Weather constraints	Heavily constrained by precipitation	None	X-band limited in persistent rain S-band continues to detect birds in light rain, performance compromised in heavy rain	Precipitation
Target	Many flocks or individuals (duck size and up) simultaneously	Bird densities	Individuals and flocks, individuals at close range	One flock or individual (even passerines) at a time
Coverage and update rate	Good	Good	Good	Very poor

Using a tracking radar enables the operator to track a single individual bird by locking the radar on to this specific target. However, if this bird passes close by a static (but moving) structure like a turbine, which will produce a much stronger echo than the bird, the radar will then automatically lock on to the turbine instead. This means again, that no tracking radar equipment currently available can be used to detect bird-turbine collisions directly.

The radar data on avoidance behaviour (especially during poor visibility) is indispensable for populating the avian collision probability models and for understanding the bird's perception of such man made structures in offshore areas and their directional responses to them. Understanding the species specific avoidance behaviour of birds to offshore wind farms is the only way in which data can be gathered to populate predictive models to contribute to EIA and the future planning of new offshore windfarm sites. Counting collisions per turbine per year (as has been undertaken at the vast majority of studies conducted at land-based wind farms) will not enable a pre-construction assessment of the local effects of a proposed windfarm since such data are highly site specific. Species abundance and composition will vary considerably between sites and local topography (e.g. coastline or bathymetric conditions) will have a substantial impact on the nature of bird movements and volume through a given site, and hence, on the number of collisions. Although birds cannot currently be identified to species by the use of radar, the echoes can be divided in to groups of birds having the same flight speed.

Vertically mounted surveillance radar can collect data on flight altitude but two antennas are needed for scanning in vertical and horizontal modes simultaneously. With this configuration it is very difficult to correlate the data from the two, independent radars. In addition, it is clear that for the measurement of altitude frequencies less than between 25-50 m above the sea surface, sea reflectance clutter will result in an underestimation of the migration volume (Hüppop et al. 2004, G. Nehls pers comm., D. Todeskino pers. comm.). That said, the experience of the Central Science Laboratory group using Furuno S-Band and X-Band radar over seascape suggests that the 50m band of interference above the sea surface from wave clutter may be over cautious with the Bird Detection Radar unit that they use (R. Walls *in litt.*). Their experience is that the level of sea-clutter does increase with increasing sea state, especially using a 3 cm wavelength radar as opposed to a 10 cm S-band over water. The group post-process all returns from beneath 5 m and exclude these from any analysis, as sea-clutter interference of some degree is inevitable. They report "…tracking is indeed affected by wave clutter and masking of bird targets through wave clutter does increase with increasing sea state and associated conditions of wave height, wind speed and tidal cycle. Below Beaufort Force 5, tracking of bird targets can continue effectively and data can still be gathered. At Beaufort Force 0-4, accurate tracking can occur down to very close to sea level, dependent on range, species and numbers. CSL therefore have taken a precautionary approach to these data and do not include targets beneath 5m over the sea-surface to avoid wave clutter interference. They also only include bird targets tracked for a minimum of 5 consecutive rotations." At Beaufort five or above "…heaped seas, wave troughs and spray can cause large-scale masking of birds using marine radar for detection close to the coast." Making offshore observations "…from a jack-up platform, breaking sea-clutter is reduced and only sea-swell is encountered for the majority of the time interference is therefore reduced further." (R. Walls *in litt.*).

In these situations (when measuring the flight altitude of birds), infrared imagery generated by TADS may offer some additional utility, especially since objects can potentially be identified to species using this equipment over this altitude range (see elsewhere).

Flock size can not be assessed from radar studies since distance to the objects, meteorological conditions and the flight altitude of the bird flocks also have significant effects on the size and shape of an echo.

If the right platform for mounting the surveillance radar and housing the radar operator is there this technique is easy applicable in offshore areas and under conditions of darkness and poor visibility in the absence of precipitation.

Limitations of current radar systems used for bird detection

As discussed above, the most effective radar systems currently used for carrying out EIAs for offshore wind farms use marine navigation radars. They have the advantages of low cost, they are readily available, offer a range of performances and there has already been significant research carried out using such radars for bird detection. In their simplest form they consist of a single radar used for horizontal surveillance where the data is taken directly from visual observation of the radar screen backed up by visual observation. More sophisticated, avian laboratories use horizontal and vertical radars with automated data collection and processing. For example, using their avian laboratory equipment, CSL have detected passerine flocks in autumn using 30 kW S band radar at ranges over 10 km and individual passerines can be detected at less than 4 km. Degradation due to precipitation is dependent upon radar type, X-band (3 cm wavelength) being much more sensitive than S-band which will continue to track accurately at >5 km (R. Walls in litt.). However, all these systems have limited performance in one form or another.

The range resolution of marine navigation radars is, at best, 10-15 m and, at worst, 200-300 m. Whilst by conventional radar standards 10 m is good, it is not necessarily good enough to detect and discriminate very small targets particularly against stronger targets such as clutter. Appendix 9.2 shows that for an X-band radar, even in the presence of light rain, detection range can be reduced by a factor of two on short pulse mode and a factor of nine on long pulse mode. At 10 m resolution the ability to count the number of birds at short range is quite good. However, it is a feature of most pulsed radars and certainly of marine radars, that the resolution becomes coarser as the range setting is increased. Some radars can be used in short pulse mode at settings up to 6 km but the detection performance in this mode is poor because the average transmit power is lower than on long pulse mode. In summary, marine radars can only achieve good resolution at short ranges, typically up to 3 km and can only achieve range detection performance with poor range resolution and high susceptibility to rain degradation.

The technology used in marine radars dates back to the 1960s. The marine radar market is very competitive and the trend is to reduce cost rather than improve performance, which is already acceptable. Consequently, the radar detection performance is poor by modern radar standards and workable ranges for carrying out EIAs are typically 10 to 15 km. For Round 2 offshore wind farms, the range from shore can be as great as 50 km and so there is no alternative but to locate on an offshore platform or alternatively on a large (>40m) ship. The more sophisticated avian laboratories have been designed primarily for operation on land and, as such, there has been no drive to minimise size. As a result, most avian laboratory radars are the size of a horse trailer or a medium sized van and can be very expensive to field offshore, requiring large jack-up barges. The CSL system has been deployed once offshore using a stable SEACORE Skate 2 jack-up platform, costing c.£10,000 per week. It is also essential to co-ordinate direct observations by ornithologists of the tracking areas involved for species verification, flight height confirmation, etc., and stable platforms offer an ideal location for this. As suggested above, a significant size reduction can be achieved by mounting only the radar head(s) on the fixed (expensive) platform (such as a weather mast) and by placing the computers and operator workspace on a boat moored alongside.

The rotation rate of marine radars is fixed, typically at 24 rpm. For optimal detection of small targets it is desirable to dwell on the target for as long as possible compatible with the required update rate. The range detection performance of a marine navigation radar used for bird detection can be improved by slowing the radar scan, probably to about 6 rpm. However, reducing the rotation rate will inevitably reduce the update rate, which could affect the detectability of the echoes in situations of mass migration events.

The elevation beam shape of a marine radar is fan-shaped, designed to cope with the roll of the ship. It is typically 20-25° wide at the 3 dB points, which is excessive compared to the required coverage, say, 10° to 15° from a fixed offshore platform. Narrower beam width corresponds to higher antenna gain, which in turn leads to better range performance. The benefit is proportional to the square of the antenna gain and so the marine radar is throwing away detection performance due to its non-ideal antenna. Also, the IF amplifiers in marine radars are usually poorly matched to the bandwidth of the transmitted signal and, again, this leads to non-optimal performance.

Conventional marine radars, except for some very expensive radars used on large ships, operate non-coherently. This means that they cannot be used to implement coherent MTI, which would substantially eliminate the problem of seeing small targets against background sea and rain clutter. Also, they cannot be used in a simultaneous range/Doppler mode, which would assist in wing beat analysis and hence better species recognition.

Marine radars are equipped with settings to eliminate sea clutter and rain clutter. These have the secondary effect of eliminating many bird detections. Therefore, the statistical analysis of the number of echoes collected on different settings is incompatible. However, if the raw radar data are used (like the Merlin software does) this limitation is overcome.

Marine radars in horizontal scan mode cannot measure the altitude of birds but they can be mounted vertically to scan a vertical hemispherical plane. Attempts have been made to correlate the target detections between horizontally and vertically scanning radars but this has achieved very limited success. The main problems are that the vertical scan radar cannot be automatically rotated in azimuth and so birds do not necessarily intercept the vertical radar's beam, and the timings and scan rates of the radars are not synchronised. This is a significant limitation for EIAs after the windfarm has been commissioned because the vertical scan radar cannot track the change in a bird's height of flight as it approaches and enters the windfarm. Hence, whilst it is possible to construct height frequency distributions of bird altitudes from this type of approach, it is difficult to assign heights to specific azimuth tracking of conventionally mounted radar.

The facility to collect and analyse target data from an unmodified marine radar is very limited. Techniques where results are transcribed from visual observations of the radar screen are useful for a visualisation of migratory tracks but, because the amplitude of radar returns cannot be recorded, they are very limited in providing information of bird count except where the returns can be confirmed visually. More sophisticated systems use the radar video from the radar to record the amplitude profile of targets directly to computer. This provides better opportunity to estimate bird count and is a far more automated process, which is less prone to human error. However, great care must be taken in the signal processing to ensure that the $1/R^4$ range factor of the radar equation is correctly adjusted for and that all the radar settings are known to the processor. Various research groups have developed algorithms to optimise the analysis process but, because these are proprietary, details are sparse in the open literature. However, it is well known that if there are limitations in a radar's performance it is far better to improve the radar's front end (the microwave and IF circuitry), or completely re-design the radar, than to try to compensate for the limitations in signal processing.

The design of a radar dedicated to the detection of birds for offshore windfarm EIAs

Previous sections have concluded that the favoured current option for carrying out EIAs for offshore wind farms is to use adapted configurations of marine navigation radars. However, it has also been illustrated that these radars are significantly limited in performance and range particularly for Round 2 wind farms, which necessitates offshore deployment. It is therefore worthwhile to consider how the performance can be improved by designing a radar specifically for this application using emerging technologies.

What is clear from the start is that all radars applied to ornithological problems have essentially used equipment designed for other purposes which are then adapted to gather data on birds. In many cases, the antenna, hardware and software have been designed for a completely different purpose than gathering data on birds. It is also clear from the discussion above that a military, combined search and multiple track radar system would be excessively expensive for this application and probably wouldn't be licensable for non-military applications. A Doppler system that can measure wing beat signatures to try to identify species is severely limited in spatial coverage and fulfils only a small part of the EIA 'wish list'. The best solution, both technically and economically, is a surveillance radar with an additional capability to measure height. For this reason, it would seem most effective to design a radar specifically with bird detection in mind from the start, rather than compromise on utility. The most effective strategy would therefore be to think in terms of substantially improving the performance of the radar front end, and approach the design of such a radar to fully utilise all of the radar target data in the signal processing.

In Appendix 9.1 seven potential radar frequency bands were identified. Frequency bands above 30GHz can be rejected because of the excessive atmospheric attenuation, which limits the effective detection range of a single large bird to less than 2km, and the effect of rain makes this even worse. This leaves frequencies at S-band, X-band and Ka-band and the choice is then determined by considerations of size and performance. At S-band high transmit powers are available, performance in rain is good but the antenna is relatively long, typically 10ft. At X-band, the radar is more compact but techniques would be required to mitigate the effects due to rain. At Ka-band, the radar is even more compact, the effects of rain are slightly worse but can be mitigated as easily as at X-band and a significant improvement in range resolution is feasible. However, there is a licensing issue because the band is occupied by the MoD. In summary, X-band and Ka-band are favoured frequency bands for this application.

As mentioned earlier, conventional pulse radars are compromised by a trade-off between range resolution and detection range – they achieve either good resolution over a reduced range or *vice versa*. Modern radar techniques can overcome this problem by transmitting a continuous wave (CW) type of waveform, which combines low peak power with enhanced performance, especially range resolution out to maximum range. CW radar measures only Doppler so it is necessary to apply phase modulation or frequency modulation to the signal to determine target range. These techniques are now quite mature and are implemented in military and commercial applications alike. A major advantage of CW type radars is that, because radar performance is related to average transmit power, they can be designed to transmit peak powers of the order of watts rather than kilowatts. Range resolutions down to 0.25m are achievable and it is possible to maintain the same resolution at the maximum range that the radar is instrumented to.

Implementation of coherent radar operation is the only viable solution to: (i) the elimination of rain clutter, (ii) species identification and (iii) improved detection performance (and hence range) over a non-coherent radar. Traditionally, coherent radar operation is associated with significant increased cost. However, improvements in transmitter designs, particularly those based on CW type radars and advances in signal processing make this achievable at acceptable cost. Coherent operation is easier to implement at low radio frequencies (RF) but would become difficult if the frequency was chosen above Ka-band.

The main challenge in designing a dedicated bird detection radar is in providing height information. As discussed earlier, using an additional radar for height information is viable but there is difficulty in correlating results from both radars. The ideal solution would be to design a single, 3D radar. One technique would be to implement multiple narrow beams in elevation (stacked beams) each with its own receiver. This is a very expensive approach and introduces a high signal processing load because of the need to correlate the target returns from all of the receivers. Another technique is to design a monopulse feed in elevation. This works by producing two overlapping beams in elevation and, by processing the returns to determine their relative power, the relative position between beams can be determined. Again, this is an expensive option and without detailed analysis it is not certain that it can provide the necessary height accuracy. A third solution is to mechanically step the elevation beam during each 360° rotation, for example in an upward spiral. This increases the number of moving parts and decreases the update rate (re-visit time).

None of these solutions is ideal and each requires significant research and/or expense. An alternative approach is to supplement the main surveillance radar with a vertically scanning radar but, unlike with the present systems, allow it to be steered in azimuth. For this system to be effective it is necessary to 'slave' the vertical scan radar from the surveillance radar. This requires the surveillance radar to incorporate tracking algorithms so that it can predict target trajectory and instruct the slave radar to steer to that azimuth. The slave radar can then either take a 'one hit' measurement as the bird flies through the beam, or, with more sophisticated processing can continue to track the bird. This solution can provide height information both outside and within the windfarm area and is a lower cost solution and lower risk solution than the three, single radar solutions mentioned above.

Further improvement over existing marine radars can be achieved by changing the rotation rate. Most marine radars have a fixed rotation rate of 24 rpm, which typically provides 10 to 15 pulses on the target for each rotation – in radar terminology, 'hits per dwell'. This is satisfactory for the large radar targets that the radar is designed for but is not ideal for detecting small targets. By increasing the hits per dwell to 40 or 50 pulses the radar detection range can be improved because effectively the target is illuminated by more transmit power. Clearly this slows the update time between scans but a balance can be achieved where detection is improved whilst not degrading the performance of the tracking algorithm. The update rate can be improved, depending upon the radar-windfarm geometry, by changing from a continuous 360° rotation to a sector scan whereby the radar scans only over a limited angle.

Finally, consideration should be made to the environmental conditions and practicalities of operating on an offshore platform. The ideal solution is to co-ordinate with the relevant wind power company at an early stage to ensure that the offshore platform or meteorological mast is designed to accommodate the radar, preferably in a position that has an uninterrupted field of view. The radar will need to be protected from the weather and sea spray. For a surveillance radar the alternatives are to enclose the complete radar head in a radome or to use the marine radar solution, which protects the antennas, turning gear etc. separately. In either case it is quite likely the electronics will need to be maintained in a temperature controlled environment. If space is at a premium the radar video signal can be taken off the stable platform to the processing system which could be housed, together with the operator station in a boat moored alongside. This has the advantage of minimising platform cost and has a secondary advantage that the processing system could be used at several different radar sites.

The table below provides a provisional specification for a radar dedicated to the detection of birds and subsequent statistical analysis in an offshore windfarm context. All of the technical specifications are currently feasible, but it would require substantial investment to implement all of them (£200,000 to £500,000 depending upon the precise specification and the amount of algorithm development, testing and verification required).

Table 3.1.2. Provisional outline specification for a dedicated bird detection radar.

Parameter	Suggested specification
Waveform	CW type, e.g. Frequency Modulated Continuous Wave Fully coherent
Mean transmit power	10 W typical
Operating frequency	X-band or Ku band
Range resolution	3m typical – out to maximum range
Instrumented range	30km typical
Height resolution	2° in elevation (100m @ 3km, 350m @ 10km)
Detection performance 0.01 sq m Swerling 1	4000m minimum (clear weather) 3500m minimum (10mm/hr rain)
Algorithms	Tracking Rain backscatter rejection Sea clutter rejection Wing beat analysis (amplitude and Doppler spectra) 3D location
Scan	Full 360°, sector scan, slow speed tracking scan for wing beat analysis)
Rotation rate	6rpm typical, 24rpm maximum
Size	Compact (antenna 2.5m, other 1m cube)
Target cost (10 off)	<£200,000
Other	Fully automated data recording Wireless transmission of post-processed data Fully weather proofed

Conclusions

Given the objectives set for remote sensing equipment established in section 2.1, the system most able to provide 2-dimensional descriptions of bird trajectories (either in horizontal or vertical mounted phases) are the low-powered surveillance radars. These radars are the most appropriate for application to avian studies in relation to single offshore wind farms at present because of their robustness, flexibility, current costs and simplicity of operation. This class of equipment offers relatively low cost system solutions, which are far more feasible to mount and operate on remote platforms than either tracking or Doppler weather radars, if these are to be bought specifically to contribute to studies relating to offshore windfarm EIAs. However, it must be stressed here that in the near future, greatly enhanced radar capacities may offer enhanced capabilities and strategic and larger-scaled radar studies will most probably be initiated in Europe and North America. These are specifically aimed at gathering information on the general migration patterns in different regions for enabling a more strategic and scientific-based planning process in relation to the future siting of large offshore wind farms. For these more strategic studies, operating at substantially enhanced spatial scales, high-powered tracking and Doppler radars might prove far better options. The following sections will exclusively deal with collection, storage and interpretation of low-powered surveillance radar data.

3.1.2 Designing a study

Platform deployment methods

Operating the radar from land will inevitably necessitate the use of extended operational ranges (normally restricted to <12 km by the use of marine navigation radar, see Table 3.1.1) if movements of birds in association with offshore wind farms are to be studied. The requirements of such a mounting will include:

- a safe and preferably stable operation platform
- easy deployment
- readily available power supply
- ease of deployment of an associated mobile laboratory
- low cost
- rapid repair opportunities and ease of maintenance
- flexibility to choose optimal mounting height to minimise radar clutter.

The alternative offshore deployment greatly reduces the need for the extended operational range of the equipment, but poses other challenges to successful and cost-effective deployment. Using a ship or fishing vessel as a radar platform has the major advantage of the very flexible siting possibilities. However, the instability of a ship at sea will often make radar observations of birds more or less impossible due to sea clutter without employing methods to remove this problem. Sea clutter problems can be greatly reduced by a fixed antenna mounting and flexibility in the mounting height above the water surface. Also, the ability to change the position of the elevation beam pattern can help to reduce the effects of sea clutter. However, the restricted availability and/or extremely high hiring costs will always limit the use of jack-up barges or oilrigs as stable radar operating platforms. The normal run up procedure to constructing an offshore windfarm will involve the erection of a meteorological mast, often several years in advance of the turbines. Such masts are themselves frequently the cause of substantial capital investment to meet other objectives, so the extra costs of planning radar elements may represent a modest proportion of expenditure when planned at an early stage. Although these masts will almost certainly have limited space for the radar and its operator, they are often sited in very appropriate areas in close proximity to the precise site of the future windfarm. Due consideration should therefore be given to the provision of radar facilities (including temporary observer accommodation, power supply and fibre optic shore links) at such structures as part of the EIA process. This could include mounting the radar antenna on a fixed mast whilst housing power supply, observer accommodation and viewing facilities on an adjacent moored boat.

The primary objective of a radar study is to describe the general movement through the vicinity of a windfarm (either as an assessment of intensity of bird movement, or as a baseline for assessing the barrier effect post construction). For this purpose, conventionally mounted azimuth surveillance radar may be sufficient. However, in most situations, there is a need to describe the 3-dimensional trajectories of birds to fully assess the avoidance reactions and assess collision risk. This does not necessarily necessitate deployment of complex radar equipment, since an assessment of the routes taken by birds using azimuth surveillance can be combined with vertical mounting of conventional radar to provide a frequency distribution of altitudes adopted by flying birds. Hence, marine navigation radars can be used to collect data on both the spatial and vertical distribution of migrating birds if both the vertical and horizontal operating modes are being used. This has to be considered when designing the study such that either a flexible-mounting device can be deployed or, preferably, two independent radars can be used, mounted in the appropriate modes.

Some method of verifying identification of the species of a sample of the birds creating the radar traces is essential. This is most easily achieved by simultaneous visual observations (using telescopes and a radio linked human observer to advise on speed and bearing from the observation point) that locate birds/flocks responsible for generating radar traces. In the absence of such visual confirmation of identification (e.g. at night or in poor visibility), flight speed (calculated from the radar traces see below) can help clarify the possible species or species group concerned.

The individual calibration of radars is the topic of much discussion, and for the purposes of this report, it is judged far beyond the scope of this document to produce effective calibration algorithms or guidance for the different radars. Radar settings, optimal operational settings and full calibration is highly dependent upon site and operating conditions and necessitates accumulation of experience at the local level. What is clear is that under a wide range of operational conditions, detectability of birds and clarity of tracks diminishes with increasing distance from the antenna source. This is a general problem that can only be tackled at the individual case study level with field experience. The general problem can be overcome in two ways. Firstly, it is possible to simply exploit the data set available and base the analysis on individual tracks once established on the GIS platform, leaving out any analyses of bird densities. Alternatively, if it is felt that modelling of bird densities is an important prerequisite of the analysis (e.g. for showing that a proposed windfarm lies well outside the sea areas of highest bird migration traffic) it is possible to model the decline in detectability of birds. This is possible using standard Distance Sampling software (see Appendix 9.5 and Programme DISTANCE, see http://www.ruwpa.st-and.ac.uk/distance/ Buckland et al. 2004). The key issues when dealing with radar calibration are: 1) accuracy in distance measurement, 2) maximum detection distance for a given bird size (e.g. using realistic dummies attached to a kite), 3) maximum vertical angle for bird detection (verification of the shape of the radar beam), 4) the effect on detectability of the in-built filters, 5) performance of different radars from which data are to be compared, and 6) decreasing performance with operation time due to reduced power of the magnetron.

A discussion of calibration techniques using calibrated targets and targets of opportunity is given in Appendix 9.6.

3.1.3 Data storage and interpretation

Bird echoes on the radar monitor appear as discrete dots moving at different velocities, which by virtue of the time delay mechanism built into the system generate temporary tracks. Ideally, all radar data should be logged automatically, saving parameters directly into a database (such as Microsoft Access) to avoid labour-intensive data transfer, observer bias, subjectivity and error. Bureau Waardenburg and CSL avian laboratory systems use such systems to feed directly into the GIS platform for analysis of complex spatial data. Such automated data transfer systems need to be very carefully monitored and their efficacy verified, but indications are that these systems are improving. However, although many ordinary marine surveillance systems have an in-built data logging system to enable saving of such tracks in electronic form (including the time trace, speed and reflectivity), the experiences in Denmark have suggested maximum utility can be obtained by manual tracing of tracks. Not least because automatic data recording still have to be proved to manage the many tracks that disappear or fade temporarily to appear again later. Such traces need alertness and interpretation on the part of the radar operator in concert with the visual observer to confirm continuity and data quality. Each individual migration trajectory can be mapped by tracing the course of bird flocks from the radar monitor onto a transparency mounted over the screen simply using a thin felt-tip pen. At all times, as many tracks as possible should be followed consistent with data quality and species confirmation, normally comprising less than 10 tracks at the same time. Periods with no bird activity should also be noted with respect to local weather conditions.

On all transparencies, the location of the observation platform (i.e. the site of the radar) and static objects must be noted and defined in relation to the tracings to ensure positional accuracy at all times. Subsequently, transparencies are digitised and entered into a GIS-database. To determine species involved for each of the radar tracks, visual observations must be co-ordinated with radar observations during day-time by direct communication between the radar operator and the visual observer.

Flight trajectories (in all three dimensions) must be stored in a GIS platform which makes further analysis very efficient (see Christensen et al. 2004, Kahlert et al. 2004). In these studies, it was important that bird movements were monitored in an area well in front of the proposed windfarm area, to generate probabilities of birds entering and leaving the proposed area pre- and post-construction.

Flight speed can be used to group the echoes into different groups of birds, since small birds tend to fly slower than larger birds. Radars produce estimates of ground speed whereas air speed is effective in identifying species. The influence of wind on the flying birds (σ: wind factor) is assumed to be a function of the wind direction in degrees (w), wind speed in m/s (W), flight speed in m/s (A), and the course of the flying bird in degrees (t) (Piersma & van de Sant 1992):

$$\sigma = -(W\cos(w-t) + \sqrt{(A^2 - (W\sin(w-t)^2} - A$$

By accounting for the tail wind component the air speed can be calculated from ground speed from the above (necessitating local measurement of wind speed and direction at the time of observation), and thus, be used to discriminate between different groups of bird species (e.g. water birds and passerines). It is essential that species confirmation be undertaken at least for a sample of individual tracks, based on either contemporary visual observations or some proxy, such as recorded air speed; these details need to be recorded in the GIS database of flight trajectories in association with a specific observation.

Radar tracks need to be stored in a GIS platform that enables the researcher to draw out all kinds of different parameters for further statistical analyses (see references following). CSL have developed a series of methods for displaying and analysing radar data from their avian laboratory using GIS and developed a series of routines to map traces, identify and eliminate echoes that are spurious or represent “noise” and for the S-band radar, allow plotting of discrete tracks of flocks or birds (R. Walls in litt.). Statistical tools have also been developed to take this spatially prepared dataset and characterise trends and differences in time and space at a given study site. (R. Walls in litt.). Two studies from Denmark (see Christensen 2004, Desholm et al. 2003, Kahlert et al. 2000, 2002, 2004 for full details of methods) have integrated results from marine surveillance radar and GIS to analyse data on avian migrants in a windfarm context. It is therefore recommended that, until improved techniques and experiences become available for assessment, these methods are adopted.

Influencing environmental factors are known to alter the migration pattern at a given site (Zehnder et al. 2001, Alerstam 1990, Baranes et al. 2003). In a “before and after construction (BACS)” study these effects need to be taken into account as co-variables, so the possible weather effect can be excluded as the explaining factor for a sudden change in migration pattern after the erection of a windfarm. Furthermore, if the weather (wind speed and direction, cloud base, precipitation, and visibility) is known to have a significant influence on bird migration and needs to be incorporated into probability models, for example describing the probability of entering the windfarm for a given bird flock. These should be produced in order to account for changing risk of collision due to natural viability.

3.2 Infrared imaging

All objects with a temperature above absolute zero, i.e. -273°C radiate heat, the intensity of which varies with the temperature of the source. Thermal imaging is a method by which object images are obtained by measuring their own, and reflected, heat radiation within the infrared spectrum of wavelengths between 2 and 15 µm, in contrast to conventional photographic images which result from the reflection of visible light.

Several generations of “night-vision” cameras exist. The earlier generation devices were image intensifying devices (e.g. night scopes, first, second and third generation scopes and night vision goggles), whereas the most recent generation can be bundled under the title of thermal imagers which exploit thermography to produce an image (e.g. forward looking infrared images, FLIR). Some infrared devices need external infrared light sources and these are known as active detectors, whereas those that merely passively detect the heat radiation emitted from a target object are known as passive detectors. Critical to object definition is the thermal resolution, which is defined as the minimum thermal differential between two objects (in this case, the heat signature of the body of a flying bird compared to its background environment).

3.2.1 Available hardware

Early generation models

The image intensifier devices pass incoming light through a photo cathode, a thin piece of glass coated with a photosensitive chemical which releases electrons when struck by photons. The electrons can then be amplified in a vacuum tube and passed through a phosphor screen, which reverses the function of the photo cathode, turning electrical energy back into visible light energy. The phosphor screen usually gives the scene a green hue. Because image intensifier devices amplify small amounts of light many times, they often have difficulty providing images in scenes subject to light level changes or in which intense fixed-point light sources appear. In general, all these devices are dependent on detecting and amplifying small amounts of light present.

The earlier generations of true infrared cameras were dependent upon an external infrared source to light up a scene and illuminate the object of interest. In a windfarm context Winkelman (1992) used two such infrared cameras to measure bird migration intensity between the wind turbines at her study site. Each camera (model Vistar IM 101) was mounted with two external infrared light sources, consisting of a 300 W light bulb covered by an infrared filter (0.83 ⊠m).

In a study of nest predators of thrushes Williams and Wood (2002) used a miniature infrared video camera (Fuhrman Microcam 2) and time-lapse video recorder. The observation distance was only 30-100 cm and the camera needed external infrared emitters to illuminate objects with infrared light of 950 nm of wavelength.

In the Netherlands, the WT-bird collision detection system is at present being developed based on microphones for impact detection and Mobotix AG camera for species identification (Verhoef et al. 2004). The published accounts provide no specifications of the camera, but this too, operated with an external infrared source. Two kinds of lenses were used: daytime lenses with focal lengths of 42, 72 or 150 mm and nighttime lenses (referred to as “low-light lenses”) with focal lengths of 35 or 48 mm. The system will be tested and further developed at 2.5MW land-based turbines in 2005.

New generation hardware

The new generation of equipment generally falls under the category of forward-looking infrared thermal imagers. These are true thermal imaging devices that create pictures based on the heat energy emitted by objects within the viewed scene rather than from small amounts of reflected light. The thermal imager/camera is positioned at some distance from the object, so the radiation passes through the atmosphere before reaching the camera. As the radiation is transmitted through the atmosphere, it is subject to a degree of attenuation due to particulate matter, water vapour and the mixture of gases in the air.

The radiation finally reaches the detector within the thermal camera via a lens, typically made of germanium (as IR-radiation is fully absorbed by conventional glass). The camera lens focuses the heat radiation onto the surface of heat radiation sensors. These elements are called the infrared detectors and transform the received radiation into an electrical signal, which is then amplified and transmitted to an array of light-emitting diodes that create a visible image, i.e. the thermal image (Hill and Clayton 1985).

Thermal imagers have been used extensively in industry (e.g. to detect defective electrical circuit boards and other electrical problems), and in physiological studies using thermography to detect heat differentials on the body (e.g. Klir and Heath 1992).

Non-windfarm infrared studies

Boonstra et al. (1995) tested a Inframetrics 522L and a Thermovision 210 on a variety of different bird species to assess whether the thermal technology could improve nest finding, determine nest occupancy and in general locate birds that, for one reason or another, were difficult to find. The 522L camera was a relatively old and bulky device, requiring liquid nitrogen as a coolant and it turned out to be too heavy and awkward for field use. The newer 210-camera was thermoelectrically cooled, and hence, portable and easy to handle. Boonstra et al. (1995) concluded that thermal imaging may provide a useful, albeit expensive tool, to assess nest occupancy of cavity- or burrow-nesting birds, and to determine the activity of birds in open habitat (monitoring avian bird-turbine collisions over open water can surely be ascribed to the latter).

In southern Sweden, the passerine migration pattern was studied using thermal imaging equipment with a relatively large telephoto lens of 1.45º (Zehnder & Karlsson 2001, Zehnder et al. 2001). This used a long-range-infrared system model called the LORIS IRTV-445L, (produced by Inframetrics, Massachusetts, USA). Continuous recording onto tape was achieved during 68 nights within one autumn migration period. A "video peak store" was applied which could superimpose several hours of recordings, so that birds passing the field of view would appear as individual lines of dots. This equipment was reported to be able to detect small passerine birds at a distance of up to 3000 m. Recordings were only possible on nights with either a clear or fully clouded sky. Precipitation also interfered with the recording capabilities of the equipment. The same thermal imaging device has been used in conjunction with radar to calibrate the moon watching method (Liechti et al. 1995) and nocturnal autumn bird migration along the edge of the Sahara (Lietchti et al. 2003). With an operating angle of 1.4 – 1.87º the device could detect close to 100% of all the small passerine birds passing the moon within a distance of 3000 m.

Infrared studies at wind farms

Only two studies have been published so far where thermal imagers have been used to look at the bird movements in the vicinity of wind turbines (see below). The first study was undertaken in the 1980s in Holland (Winkelman 1992) and more recently the newly developed Thermal Animal Detection System (TADS) has been used for collision monitoring in Denmark (Desholm 2003, 2005).

Winkelman's (1992) study in the 1980s used a single thermal imager camera for detecting collisions between land-based turbines and migrating birds. The long wave (8 – 13 μm) camera used was a Philips Usfa model UA 9053. Long wave cameras are less susceptible to absorption by the atmosphere than the short wave (2-5μm) systems (Desholm 2003b). The thermal resolution for this device was 0.1°C. In this study, several different lens sizes were tested (15°, 5°, and 3° lenses). The 15° lens could detect songbirds out to a distance of 50-250 m and a pigeon out to a distance of 250-300 m.. With the 5° lens, individual pigeons could be seen at a distance of 600 m., while the 3° lens could detect ducks out to a distance of 3 km. The ability of a thermal imager to detect a given object is constrained by the optical resolution and the size of the lens used. For this study no data on the former was published.

During the last three years, the Thermal Animal Detection System (TADS) has been developed in Denmark for automatic detection of avian collisions at offshore wind farms (Desholm 2003b). The current TADS configuration comprises a Thermovision IRMV 320V long wave (7-15μm) infrared spectrum camera from FLIR (new generation detectors) with a spatial resolution of 320 x 240 pixels. The TADS-camera is fitted with a standard 24° lens, but also 12° and 7° telephoto lenses were tested during the development phase. Specifications relating to the geometrical resolution and horizontal image size for the three lenses are given in Tables 1 and 2 in Desholm (2003b).

The camera was installed in a waterproof metal box with remote-controlled windscreen wiper and sprinkler system. The camera was mounted on an offshore 2

MW turbine with a pan and tilt head and the direction of the field of view could be remotely controlled. The equipment was lightning-shielded in order to secure the power installations within the turbine itself.

In the TADS application, the thermal camera was mounted in a vertical position c. 7 m above sea level to enable vertical viewing. A 24º lens was used and it covered c. 30% of the area swept by the 42 m long turbine blades.

At the turbine, a computer placed inside the turbine tower was connected directly to the thermal camera for system software handling and for temporary data storage of large digital video files.

In the current TADS system, thermal sensor software is used to start downloading video sequences onto the hard disc only when at least one pixel in the field of view exceeds an operator-defined threshold temperature level. This ensured a minimum number of recorded events so that only sequences of birds passing the field of view or colliding with the turbines were captured on the hard disk. It is a feature of obvious importance for this system that the observer can avoid arduous viewing of many hours of empty scenes in the absence of warm-bodied objects in the field of view.

Furthermore, operator-defined parts of the field of view can be excluded from the analysis performed by the TADS thermal sensor software. In this way disturbing heat radiation from e.g. parts of a wind turbine can be eliminated, by simply masking off that part of the field of view in which the turbine is depicted.

To reduce the data volume, in terms of bytes stored, as small as possible a compression programme was applied. The system can be controlled remotely and was set to start automatically after power cuts, as a connection can only be achieved if the remote control software is running.

Conclusions

In general, it can be concluded that the thermal imaging hardware available can provide data on nocturnal bird movements that is difficult (if not impossible) to obtain in any other way. For fast processing of data three options exist so far:

- rapid fast forward viewing of recordings,
- trigger software that excludes all non-bird observation periods (Desholm 2003b, Desholm 2005), and
- video peak store which superimposes several hours of recordings in to a single frame (Zehnder & Karlsson 2001, Zehnder et al. 2001).

The operational distance is much less than of ordinary video equipment due to the relatively low optical resolution of thermal imaging devices, but this can in part be overcome by the use of large telephoto lenses. However, the trade off between operational distance and the size of the field of view at a given distance should be borne in mind. This is important, since the area monitored by the infrared device can be of considerable importance to the sample size of data that can be collected by one system within a given amount of time.

Only one type of hardware arrangement (the TADS) has so far been used as a remote controlled system for offshore use. However, since this kind of remote controlled software is comprised of standard components for any operational system there are no constraints on its use, besides the necessity for an optic fibre linkage between the land and the windfarm. TADS is also the only system adapted for offshore use under harsh and corrosive (especially salt) conditions. Nevertheless, no severe problems have been encountered with regard to its offshore use and the fact that the prototype of TADS has been operating continuously under these extreme conditions for more than a year clearly shows that any possible constraints can be easily overcome.

3.2.2 Designing a study

A whole suite of considerations needs to be taken into account when designing behavioural studies of birds in relation to offshore wind farms. The siting may be many kilometres offshore from land, which gives rise to specific demands on the design of the equipment (which has been briefly considered in section 2.7).

The first level of choice concerns the decisions regarding what kind of hardware to apply in a study, but thereafter the question of where to mount the equipment becomes vital. If the thermal monitoring programme is to be conducted after the erection of the turbines only, both the turbines themselves and probably also a transformer platform situated in the near vicinity of the windfarm will form suitable fixed structures for such purpose. The usefulness of the transformer platform for mounting the equipment depends on two factors: 1) the nature of the data required and 2) the distance between the platform and the nearby turbines. If the study aims to measure the number of avian collisions directly, the platform will need to be close enough to at least one of the turbines to fall within the operational distance of the thermal imager. This depends upon the interaction between the optical resolution of the equipment and the size of the birds of interest.

The use of the turbine itself as the TADS mounting structure necessitates its use in the vertical operation mode, an approach that has already been adopted in the TADS study (Desholm 2003b, Desholm 2005). The disadvantage of this vertical mode of mounting is the limited monitoring effectiveness, due to the changes in turbine nacelle orientation (relative to the static camera) as a result of shifts in wind direction. Optimally, a mounting device that follows the front of the nacelle with changing wind direction would overcome this limitation. Such a device is technically an option but is costly and logistically complex and has, to date, not been developed or deployed. In the study by Desholm (2003b), the constraints associated with a fixed camera mounting were discovered early in TADS development process. In later trials, a pan and tilt head was applied which significantly increased the monitoring efficiency to over 60% because the viewing direction could now be changed remotely by the operator.

With the relatively low optical resolution in the existing thermal devices available on the civil market, the horizontal viewing mode from one turbine towards a neighbouring turbine will only be feasible if a large enough telephoto lens can be used. This will, as stated above, result in a very restricted field of view and thus limit the number of recordings where birds are passing or colliding with the turbines. Furthermore, since most collisions are expected to occur in situations with poor visibility, e.g. dense fog or heavy drizzle, it is highly advisable to minimise the distance between the thermal detector and flying birds, since detectability will decrease with increasing distance. It must be stressed though, that under situations of severe fog or precipitation the thermal cameras can detect flying birds at longer distances than the human eye or cameras sensitive to visible light (Desholm 2003b).

At present, the German authorities have constructed one research platform named FINO1 in the North Sea (Dierschke 2004) and another one is planned for the proposed windfarm area in the Baltic Sea. The approach of building research platforms prior to the erection of turbines makes it possible to conduct pre-construction studies combining both radar and thermal imaging. Although this approach is relatively expensive, it does provide the optimal set-up for studying the behaviour of the birds well before the construction process and provide baseline data for post-construction comparisons. In this way, thermal-imaging techniques can also contribute effectively to studies based on a BACI-type design where before-and-after construction conditions can be compared.

To our knowledge, no studies have so far been published using thermal imaging to detect flying birds from a boat-based survey, although infrared devices mounted in aircraft have been used for census of seals at their haul outs (e.g. Cronin et al. 2004).

In the Dutch study by Winkelman (1992), the turbines were land-based, and hence, the thermal camera could be easily mounted on a tripod at a preferred distance from the turbines. Compared to the present and future large offshore wind turbines (2-5 MW), the turbines monitored for avian collisions in the Winkelman (1992) study were very small. This meant that one camera, despite low optical resolution, could cover the whole area swept by one turbine.

In the case of any future offshore windfarm, online data transmission and remote controlled operation will be relatively straightforward, since high volume cables comprising optic fibres will interconnect the individual turbines, the transformer station and the Internet onshore.

Power supply for the thermal devices should not constitute a problem, since power is easily accessible within turbines or at the transformer platform. In the case of mounting on a ship or weather measurement tower, due consideration will need to be given to the subject of power supply, since this can be crucial.

The older generations of thermal cameras needed relatively large power supplies like the 6 x 0.85 kg NiCad battery pack described by Boonstra et al. (1995). The current thermal imaging market consists almost entirely of new generation thermal devices, which can be supplied with power either from small, internal re-chargeable batteries (for handheld models) or from the national power grid.

When designing a thermal imaging detection programme it is advisable that the equipment is bench- and field-tested well in advance of the initiation of the study. First of all, getting to know the effects on the visual picture on the monitor of changing camera settings is crucial, especially with regard to achieving sufficient contrast between bird and background (e.g. water surface or a clear versus fully clouded sky). Secondly, the trade-off between focal length (i.e. strength of the telephoto lens) and area of the field of view at a given distance should be taken into account when considering the distance between the thermal detector and the monitoring field area and lens size. Often, the number of possible mounting sites are limited, and hence, choosing the right lens is essential to ensure that single individuals can be detected at relatively poor resolution (because of the low number of pixels/detectors in the device). Adding a long-range telephoto lens to a thermal imager will inevitably result in a very much-reduced monitoring area. And the consequence of a reduced area monitored will be a reduced amount of accumulated data if the number of monitoring devices or time spent on monitoring is not increased accordingly. Under all circumstances, the trade-off between sensitivity and image clarity will inevitably involve considerable manual viewing in the early stages of deployment to ensure familiarity and optimal calibration at a newly established study site.

Increasing the focal length (i.e. decreasing the field of view measured in degrees) of the thermal device by a given factor will always result in a decrease in the area of field of view by the same factor squared. Decreasing the angle of view by a factor of 2 from 24° to 12° will result in a four fold ($2^2 = 4$) decrease in area of the field of view at a given distance.

In the study by Desholm (2003b), the equipment was calibrated in order to relate a given body length measured as the number of pixels at the monitor to a real life body length. The longer the distance between bird and camera the smaller the body will appear at the monitor. Wing beat frequencies can be used as a secondary cue to determine the observed bird to group or species.

Conclusions

Before designing a thermal imaging programme it is important to consider several aspects of the study. First of all, the physical structures available as potential mounting platforms (turbines and transformer platform, weather measurement towers) must be given due thought and consideration, since these and (especially) the distance between them can constrain the data collection because of the limited resolution of such thermal imaging devices. Secondly, due consideration must be given to both the species of interest (or at least the size of the key focal species) and whether single individuals or flocks of birds form the focus of the study. If small birds are the main target and single individuals need to be detected (and if collisions are to be measured directly) a large telephoto lens is required, and thus, the field of view will be highly restricted. A small field of view will necessitate greater replication (i.e. more TADS devices) if reliable collision estimates are to be produced. A low migration volume will also require a larger number of devices in order to increase the sample size of the data set.

Any study design needs to take account of the variable risk associated with different turbines and the need to obtain an objective estimation for an entire wind farm based upon samples gathered from a restricted number of individual turbines. Potentially the equipment could be mounted on different turbines in sequence. More effort needs to be invested in gathering data on the nature of near-blade avoidance behaviours for integration into collision risk modelling.

3.2.3 Data collection and storage

Data collected by thermal cameras can be used either to measure avian collisions directly or as input for statistical modelling of the risk of collisions.

When dealing with the direct measurement of avian collisions a monitoring programme must be the subject of careful design. The aim of such a programme will be to compile enough information to form the basis for a sound statistical analysis. Thus, the appropriate temporal scope and hardware volume of such investigations will be dependent on the actual number of collisions and on the spatial and temporal distribution of these at a given windfarm. If several collisions occur daily at all the turbines, a single device such as TADS would be sufficient for data collection protocol. However, if the annual collision rate amounts to 1-5 birds within a 80 turbine windfarm many more devices will need to be mounted in order to detect these few collisions to provide reasonable precision on collision risk estimates. This means that low collision risk necessitates a larger-scale monitoring programme (both in terms of number of devices and monitoring time).

The process of running a collision-monitoring scheme consists of operating the camera system over a given period of time. The degree to which the system is capable of running automatically will, to a large degree, determine the investment of man-hours needed. In the absence of automation, the operator will need to operate the camera and subsequently process all the recorded videotapes. The processing of recording can be speeded up in two ways. Firstly by fast-forward viewing of the recordings (with the associated risk of overlooking either small birds, rapid passage of the field of view to short distances between bird and camera or birds appearing small due to a very long distance between bird and camera). Secondly, by the use of a video peak store to superimpose several hours of recordings onto one frame (Zehnder & Karlsson 2001, Zehnder et al. 2001). If the bird image represents very few pixels in time and space (as explained above), the risk of missing an event during rapid visual viewing of the recordings increases significantly. Similarly, using the video peak store method, there is a risk that birds passing close to the camera will not be visible on the superimposed picture, because the time taken for the bird to pass out of the field of view was less than the time interval between two consecutive frames

For these reasons, the best solution is a system that only records imagery when birds are either passing or colliding with the turbine blades, and to date TADS is the only system that has adopted this approach (Desholm 2003b).

It should also be remembered that, when running an avian collision detection programme, it is advisable to log all activities in a logbook. This discipline ensures that data relating to monitoring efficiency, number of bird flocks passing per unit time effort, the influence of time of day and of the natural viability induced by weather on the collision risk can be analysed after the end of each field season.

Modelling collision risk

If, for one reason or another (economical, technical or other reasons), the direct measurement of avian collisions turns out not to be feasible, a more indirect approach of modelling the avian risk of collision can be applied. This approach necessitates the construction of statistical models that can forecast the number of potential future collisions that may occur at a given windfarm or windfarm site. For this modelling work, radar data describing the three dimensional avoidance response and migration trajectories will be essential (see section 3.5.1 and 4.2), however, the infrared monitoring device can also contribute important data on close range behaviour in response to turbines to these models, especially by providing the following parameters:

- near turbine blade avoidance behaviour,
- flight altitude,
- flock size, and
- species recognition (especially at night).

In many circumstances, it seems that assessing the flight behaviour response of birds to turbines is more practical and useful than direct measurement of collisions (which maybe infrequent and therefore difficult to predict with a high degree of confidence). This approach also provides the observer with an understanding of the circumstances and behaviours that lead up to a species specific collision incident.

Near turbine blade avoidance behaviour

To date, the near turbine blade avoidance behaviour of birds, which is probably species specific, has never been included in the modelled estimation of avian collision risk. An indirect way of taking this factor into account is to subjectively rank the species of interest in order of flight manoeuvrability, as was done in a recent risk assessment paper by Garthe & Hüppop (2004). Caution should be taken though, since flight manoeuvrability (the combination of flight speed and weight) is only one of several factors likely to determine the ability of birds to actively avoid a turbine blade at close quarters or a windfarm over much greater distances. Visibility, the propensity for behavioural habituation and the degree to which a given bird species reacts to the presence of turbines are all factors which, to our knowledge, have never been described or investigated, despite their potential importance in assessing avian collision vulnerability. For instance, Long-tailed ducks *Clangula hyemalis* tend to fly under the bridge at Kalmarsund in Sweden whereas Common Eiders fly either over the bridge or over the nearby island when passing on migration (Jan Pettersson pers. comm.).

Flight altitude

Flight altitude is thought to have a profound effect on the risk of collision. Obviously, birds flying mostly below or well above the sweep area of the rotating blades will experience low levels of risk exposure. Data on flight altitude of migrating birds over open marine waters must be collected both by day and night, since time of day is know to influence flight altitude in most migrants (Alerstam 1990). Although vertically mounted ships-radar have proved to be highly effective at measuring this parameter through a narrow swathe of the atmosphere, the TADS also offers some potential in this area and is at present undergoing tests in this connection. The use of TADS to measure the altitude of migrating birds relies upon geometry to estimate the vertical angle and distance between the camera and the bird. The vertical angle can be estimated by measuring the level of the bird against the neighbouring turbine (against which the bird passes), corrected for the height of the TADS above the sea. The distance to the bird can be estimated by measuring the length of the bird in pixel units which can be converted to a distance by a conversion factor if the size of the bird can be identified on the video sequence (see below).

Flock size

During the day, real time visual observation or video recordings offer the simplest way of obtaining data on flock sizes which can be used in the process of forecasting the potential number of future collisions at a proposed windfarm. However, no studies have, to our knowledge, been undertaken to compare flock sizes by day with those at night. Hence, radar studies dealing with number of flocks (rather than individuals) as the measuring unit could potentially under- or over-estimate the predicted number of collisions, if there is a significant difference between these two periods of the daily cycle. Here again, TADS offers such a means of providing such a calibration and is at present being tested to determine the ability to generate data on flock size frequency distributions during both night and day. The results so far seem promising, with resolution again the limiting factor, since flocks of birds at long distance appear as small warm moving “clouds” not distinguishable to individuals. However, even though the number of individuals within such a flock can not be counted directly the flock size can still be estimated to a high degree of certainty.

Species recognition

If the aims of modelling avian collision risk also include a species specific component, species recognition and determination by both day and night is essential. Thermal imaging offers this facility where body shape (if the bird is close to the camera), flight speed, flock formation and wind beat frequency all help the operator to categorise the observed birds to species or (at worst) into groups of similar species. Gathering of such data as these are not possible from a radar sequence.

In the previous generations of infrared cameras, storage was restricted to video camera recorder (VCR) media for maintaining a permanent record. Today’s applications can store the thermal recordings as digital files either in smaller quantities on memory cards inserted in the cameras or saved to computer hard disks where larger amounts of data can be stored (multiple single frames or many and long thermal video sequences).

To limit the data volume, an extensive suite of compression software exists. Such software must be tested before a monitoring programme is initiated, so as to compromise between the highest compression level and that at which adequate frame picture quality is maintained. The current TADS formulation includes a large hard disk at the computer in the turbine tower for data storage (Desholm 2003b). However, for data security reasons, it is recommended that frequent downloads of the sequences to a computer (via the Internet) at the office are undertaken where storage on CDs or DVDs can be achieved (Desholm 2003b).

Thermal detection systems can not only act as monitoring devices for avian collisions but also collect important data on flock size, species composition and flight altitude for statistical modelling of the avian collision risk for a given windfarm.

3.2.4 Data interpretation

Measured estimates on number of collisions

In order to scale up from the collision rate estimates determined by a few TADS to providing predictive estimates for a whole windfarm, the spatial and temporal coverage needs to be estimated from the monitoring log. Where radar data are available, the scaling up model should incorporate specific data on migration patterns, direction and intensity, instead of merely multiplying the number of collisions detected by the TADS at one turbine by the number of turbines within the whole windfarm. The migration intensity is seldom uniformly distributed within a windfarm consisting of many turbines. Hence, due consideration needs to be taken to estimate the differential risk of collision with respect to angle of attack and position of each turbine within the windfarm relative to the front edge presented to migrating birds.

Changing levels of visibility due to changing conditions with regard to time of day, fog and precipitation is thought have a significant effect on the risk of collision (Winkelman 1992, Kahlert et al. 2000). Thus, it is essential that this factor is incorporated in future windfarm studies in offshore areas.

Modelled estimates of the number of collisions

Modelling work involves the collation of the following four kinds of data using thermography techniques:

- near turbine blade avoidance behaviour,
- flight altitude,
- flock size, and
- species recognition (at night time).

Near turbine blade avoidance behaviour

For future risk assessments it is important to collect species/group specific data on the ability of birds to avoid the sweep area of moving turbine blades when approaching them to a close distance. Ideally, the goal should be to compile data to estimate the probability that an individual can perform a near turbine avoidance response when first approaching the blades for each species or for each group of species. This near blade avoidance probability should then be built into the overall probability model describing the proportion of the birds passing the study area that actually collide or have the potential to collide with the turbines.

Flight altitude

The tail wind component (Alerstam 1990, Krüger & Garthe 2001) and time of day (Alerstam 1990, Fortin et al. 1999, Diehl et al. 2003) are two factors which potentially can alter the migration altitude of avian migrants, and hence, these factors need to be incorporated in a TADS-based flight altitude study.

Flock size

It has been shown for Common Eiders, that flock size is correlated with the migration intensity (Almkvist 1975) and furthermore it could be speculated that that flock size might be affected by time of day. Hence, the effects of these two variables on flock size should be taken in to account if flock size is incorporated as a factor in a model estimating the rate of bird-turbine collisions.

Species recognition.

It is difficult to accumulate species-specific bird data in offshore areas, since the very siting (often many kilometres from land) makes the stationing of observers costly and impractical. Furthermore, species determination at night has almost never been undertaken in the context of offshore wind farms. The use of radar provides flight speed as the only available parameter upon which to base species recognition, although the use of tracking radar does enable measurement of wing beat frequency from single individuals (but this type of radar is very expensive).

Whether estimating the local effects or global impacts on bird populations of avian collision mortality through modelling, a species-specific approach is essential. TADS offers several ways to identify observed birds to species or group level. Although plumage coloration is not distinguishable on a thermal image (birds appear white at best against a dark background), body shape (if at relatively close range), wing beat frequency, flock formation, “jizz” (often indefinable combinations of species characteristics) and flight pattern can all contribute to species identification by experienced observers.

3.3 Additional observation methods

Visual observation

Using long-range spotting scopes (e.g. x30 magnification) migrating birds can be identified to species out to a distance of at least 5 km for larger birds like ducks and geese (Kahlert et al. 2000, 2002). This detection distance depends on the height above sea level at which the observer is sitting and the weather specific visibility. The fact that this method cannot be used during darkness at night and in periods with dense fog is its biggest shortcoming since these are the very periods when one would expect the highest number of collisions to occur. For this reason, visual observations can never be the sole method adopted for the study of avian collision rates at offshore wind farms. However, this low-tech method can supplement the more sophisticated methods using radar with very important specific data on migration volume, flock size and species identification at least during the hours of daylight. TADS can provide these data during both day and night, but are constrained by a restricted data volume resulting from the fixed directional field and smaller field of view.

Visual video recording equipment suffers similar limitations as spotting scopes with regard to poor visibility and is further constrained by the fixed viewing position as is TADS. Nevertheless, a video camera can be operated remotely and therefore potentially can collect data from within a windfarm during daylight every day. The use of dual pre-set video cameras viewing a common image theoretically can be used to generate position and height of a moving object, using simple trigonometry and co-ordinated image capture. Testing of such a system on a meteorological mast associated with a wind farm in UK offshore waters is currently underway (Outersight system, P. Barlow *in litt.*). Thermal imaging could potentially extend the system to function at night, currently a major shortcoming of gathering data only by day. A further drawback of this system is the many hours of recordings, which have to be visually viewed, although this could be done remotely at the office and could maybe be simplified by the use of automatic pattern recognition software if this could be developed in the future.

Avian acoustical monitoring

Detecting bird sounds using microphones in the vicinity of turbines offers two sources of information to tackle two different issues. Firstly, monitoring of bird calls for species recognition and secondly, monitoring the sound of birds colliding with wind turbines as a means of measuring collision rate.

Acoustic species recognition

Sensitive microphones aimed at the night sky are used in recording the vocalisations of night-migrating birds. The technique of acoustic monitoring of avian night flight calls is a way of producing a list of species of birds migrating over a given site at night. The relative volume (detection rate) at the species level can be obtained (Farnsworth et al. 2004), but such data will always be biased towards species using contact calls during nocturnal migration and fully exclude those species that do not.
From studies in North America, some 200 species are known to give calls during night migration of which roughly 150 are sufficiently distinctive to identify with certainty (Evans 1998). The remaining species can then be lumped into a number of similar-call species groups. The acoustic data on tapes can be either processed by ear or analysed by sound analysis software (Evans 1998).

Acoustic monitoring of collision rates

Presently, the ECN in The Netherlands are developing a bird-turbine collision system based on microphones linked to a video camera monitoring the outside of the turbine (Verhoef et al. 2004). The system aims to detect the acoustic signal created by birds hitting the turbine structures. The microphones are placed on the inner side of the turbine tower and the acoustic data are continuously analysed by sound analysis software. The system is not operational at present and some major problems have not yet been solved. For example, the background noise of larger turbines far exceeds original expectation, hence, the signal from bird collisions cannot be separated from background mechanical sounds. Furthermore, there are several shortcomings associated with the camera, because the quality of the night time images has been insufficient for species recognition, necessitating excessively long exposure times.

Laser range finder

A laser range finder can be used to measure the distance and vertical angle to an object and thereby estimate the height. Furthermore, the horizontal angle can be obtained also in some devices which in combination with the distance to the object and the geographic position of the observer can give a three-dimensional position of the object. Several consecutive positions of an object, e.g. a migrating bird can in this way be used to describe its migration trajectory. The drawback of this method is that it can be operated only in daylight and the spatial resolution is relatively restricted. However, it offers an alternative to radar measurements of flight trajectories if the target bird species (i) offer a sufficiently large cross-sectional areas target for the laser and (ii) migrate at a relatively short distance from the observer. Such techniques are only possible to deploy during daylight periods to supplement other approaches.

Ceilometers

Ceilometer surveys involve direct visual observation of night-migrating birds using a high-powered light beam directed upward from a study site (Able & Gauthreaux 1975, Williams et al. 2001). Birds will appear as white streaks as they pass through the beam and must be view through a spotting scope or binocular. In general, this method allows birds as small as thrushes to be detected and counted out to a distance of up to 1,200 feet from the observer. Data can be collected on total numbers of birds passing the beam and can then be used to estimate an overall passage rate for the site. Furthermore, the approximate heading of the migrating birds can be assessed. In a windfarm context, this method can be used to describe the species composition during night time migration.

Moonwatching

Moonwatching is a similar technique to the ceilometer where the light beam is exchanged by the full or nearly full moon. Otherwise this technique follows the procedures used in ceilometer surveys (see above). Moon-watching can be a useful adjunct to ceilometer-based studies, since ceilometer beams are difficult to see on bright moonlit nights.

Casualty collection

Collecting the dead and crippled collided birds at offshore windfarm installations has so far never been tried and is judged to be unrealistic due to the often strong currents (which would remove corpses away from the vicinity of the site) and due to the unknown scavenger rate. Construction of floating bunds and/or nets to retain the corpses is expensive and impractical and would not overcome problems associated with predator scavenging over longer sampling periods.

3.4. Pros and cons

As can be seen in the overview presented in Table 3.4.1, the different remote techniques all represent some capabilities and some limitations. Thus, when the overall aim of a given study is agreed the designing process of choosing the best combination of methods can begin.

3.4.1 Radar

Low cost marine navigation radar offers presently the best, but far from perfect, solution for accumulating probabilities for bird movements within wind farms and for predicting bird collision rates. It does not, nor is ever likely to, offer a means of counting collision events. However, its extensive ability to track birds/flocks in three dimensional space at a spatial scale that enables the measurement of bird traffic pre-windfarm construction and avoidance post-construction makes this a potent tool for developing risk assessments for such developments. The use of such simple technology does have several disadvantages, namely the difficulty of identifying radar tracks to species without visual confirmation and the need for horizontal and vertically mounted antenna to derive maximum spatial data on bird distributions and altitudes. In addition, the problems associated with precipitation and radar "clutter" associated with reflections from waves and turbines, constrain its effectiveness in poor weather and when deployed on ship platforms. Also, radar single echos comprise both individual birds and gathers flocks of different size, hence the actual volume of birds needs visual calibration of a sample of radar tracks. Nevertheless, the ability of radar to collate spatially explicit data under a range of meteorological and visibility conditions (including complete darkness) and the ability to find practical solutions to less than optimal configurations make the general approach the method of choice under all circumstances.

Some features (such as flock size) will probably always be beyond the capability of radar, but the rate of development in software and hardware in recent years makes vastly improved utility possible with modest investment in future years. It is to be hoped that major developments in the field in coming months will enable new and exciting applications that greatly improve on currently available hardware and software configurations.

3.4.2 TADS

At present, TADS is the only remote technique for detection of bird-turbine collisions that is fully developed for offshore use. At the time of writing no collisions have been detected after 664 hours of observations. The ability to observe birds passing the turbine at close range or actively avoiding the rotor-blades makes it a very promising tool with regard to detect collisions and recording level 3 avoidance behaviours (see table 2; Desholm 2003b, 2005). Furthermore, TADS is also the only practical remote sensing tool available to assess the efficacy of stopping turbines blades as mitigation to reduce collision mortality under conditions where this is expected to be unacceptably high.

TADS offer better opportunities than radar for species recognition since shape, size and wind beat frequencies of the birds can be assessed. This is especially important at night and under conditions of poor visibility.

For the probability models aiming at describing the collision risk at different scales TADS is the only system that can collect data on level 3 avoidance behaviour in conditions of poor visibility. Furthermore, TADS can produce input for these models in terms of data on flight altitude (coarse data), flock size and species involved.

TADS can operate just as well during dark nights as in full daylight and therefore fulfils one of most important requirements for a collision monitoring device. In situations with severe precipitation like snow and rain the TADS performs better than the human eye (Desholm 2003b), but less well than during dark nights. Data presented in Desholm (2003b) showed the relative detectability of warm focal objects as a function of visibility due to darkness, fog and snow.

TADS has been shown to perform extremely well under the often harsh and salty conditions prevalent at an offshore windfarm with no severe problems occurring during more than one year of operation.

The biggest disadvantage of the TADS is the high cost of c. £40,000 per device, which can then only cover c. 1/3 of the area swept by the rotor-blades of one 2.3 MW turbine.

3.4.3 Visual

A visual observer can detect and count collisions at offshore wind turbines if he/she can be positioned on a safe viewing platform nearby from where it is possible to undertake the observations. Visual observations are obviously restricted to ranges of a few kilometres, up to 6km only under exceptional conditions of visibility, for certain species. This holds only for daylight hours with good visibility and this is the major constraint, since collisions will most likely occur in conditions of poor visibility. Since bird-turbine collisions are, by their very nature, rare events, many man-hours of observations are needed. No trigger software (as with TADS; Desholm 2003b) or video peak store (as the Swedish study; Zehnder et al. 2001) or fast viewing of video tapes (as the Dutch study; Winkelman 1992) can be applied to the visual observations to limit the amount of man-hours needed.

When it comes to species recognition of flying birds, the human eye is probably the most reliable available tool but its use is restricted to daylight. The method of watching the full moon for passing birds is a very much used technique throughout the US (but see also Liechti et al. 1995), but it only provides a description of the species passing the area, without contributing data on the spatial relationship between the birds and turbine sweep areas.

For the probability models aiming at describing the collision risk at different scales, the visual observer can collect data on whether the birds are avoiding the windfarm, turbine or rotor-blades or not. Again, this only holds for daylight and conditions without precipitation.

The costs and demands for housing a human observer at an offshore installation is far more complicated and expensive than for mounting remote sensing hardware (such as video camera, TADS or microphones) with a optic fibre link to land. This extra cost, together with the man-hours needed, and health and safety, must be taken in to account when designing offshore windfarm-bird studies.

Nevertheless, the use of all remote sensing techniques still require some human observations to calibrate equipment and provide supplementary species verification in order to obtain maximum effectiveness from the use of such techniques.

3.4.4 Acoustic

For measuring collisions directly acoustic monitoring may offer a promising solution but the technology is still under development. The most significant limitations will be that neither the avoidance response of the birds to wind farms, turbines, or rotor-blades nor the mortal injuries caused by the vortices produced by the moving turbine blades (which contribute to mortality but which cannot be detected by this method) can be registered.

For determining the species composition of the migrants aloft at a given site the automated registrations of flight calls by microphones offers a well-documented method. The rate of calling (measured as calls/hour) by nocturnal migrants have even been shown to correlate with the density of migration measured with Doppler radar in the US (Larkin et al. 2002), and this application can therefore also produce a relative measure of the temporal migration volume for different bird species. The method is constrained by the fact that not all bird species call during migration and by the limited distance at which the equipment can record the calls. In reality, this distance is considerably less that for the vast majority of passerine migration passing a windfarm. However, this method could provide a relative measure of temporal migration volume, contribute to an assessment of species composition and even to some degree contribute to defining spatial migration patterns if several microphones are used (Larkin et al. 2002). Furthermore, if more microphones are used in an array it might be possible to estimate the flight altitude of those birds flying within the detection range of the applied microphones. Hence, this method could prove more successful in the future given enough investment in research and development.

However, at present, acoustic monitoring cannot presently provide data on flight altitude nor flock size, and its use may also be constrained by the surrounding back ground noise produced by the waves, rain or the rotating turbine blades. The collection of data by microphones is largely unaffected by heavy fog (although this may affect attenuation) or during darkness at night.

Compared to the other remote technologies described in this report the acoustic monitoring is a relatively low cost application, but requires more research and development to produce more effective tools for application in this field.

Table 3.4.1. Overview of the pros and cons for different types of remote techniques for observing bird behaviour in relation to offshore wind farms. "Radar" covers marine navigation radar and tracking radar, "TADS" all thermal detection systems, "visual" covers both data collected by human eye and ordinary video camera, "Acoustic" covers both acoustic bird call recording and microphone collision monitoring. Level 1 in avoidance behaviour refer to the probability of a bird's avoidance of a windfarm, level 2 of turbine and level 3 of rotor-blades.

	Radar	**TADS**	**Visual**	**Acoustic**
Detect collisions	No	Yes	Yes	Under development
Avoidance behaviour	Yes (level 1 and 2)	Yes (level 3)	Yes (level 1 (limited for large wind farms), 2 and 3)	No
Species identification	To some degree (groups)	To some degree (groups)	Yes	Yes (bird calls) / no (collision hits)
Flight altitude	Yes (vertical ship-radar or tracking radar)	Yes (coarse data)	Yes (constrained for offshore areas)	No
Flock size	No	Yes	Yes	No
Operational under poor visibility	Yes (fog and in dark) / no (precipitation)	Yes (in dark) / to some degree (fog and precipitation)	No / yes (ceilometer and moon watching at night)	Yes
Offshore use	Yes (personal platform needed)	Yes (platform needed)	Yes (personal platform needed)	Yes (platform needed)
Hardware costs	High / very high	Very high	Low	Medium

4. BEST PRACTICE GUIDANCE

In view of the developmental nature of the technologies under review, this guidance will be a working document, to be modified in the light of field-testing and as part of an iterative process to improve the performance of equipment and hence improve best practice guidance. In particular, the guidance presented here relies heavily on experience from just two major worked examples from Denmark. It may well become apparent from other future projects that these examples are not representative of a broader range of studies. For example, much emphasis here is placed upon the movements of migrating birds, but in the future, it may well be that local bird movements may represent the primary interest and therefore present a different set of challenges to effective development of EIA guidelines. For this reason, it is envisaged that the guidance will need review and update in the light of experience.

The overall aim will not necessarily provide a recipe book approach to the use of remote technologies, but rather guide on best practice under the prevailing circumstances.

4.1 Framework for the EIAs

At this early development stage of the offshore wind industry only limited information exists from studies dealing with offshore wind farms and birds. Therefore, it is too early to apply results from existing studies to new EIAs, and hence, although generic guidance is sometimes available, all data required to make an appraisal of environmental impacts must be gathered at the proposed site. However, financial resources are always limited and a careful prioritisation process must be undertaken to initially focus on the species that are most likely to be affected by a new windfarm and on those species that occur in such high numbers that statistically robust conclusions about the impact can be drawn from the collected data. In brief, the minimum data needed for a proper EIA includes gathering radar data on bird movements in the vicinity of a proposed windfarm, for describing the large scale avoidance behaviour and for input in a probability model describing the collision risk. Such predicted collision risk should be assessed post-construction by some means of direct measurement of the number of collision casualties where possible (e.g. with the use of TADS). This is especially important for gathering species-specific data on small-scale flight avoidance behaviours of different birds.

Ideally, a formal post-construction monitoring and mitigation plan should be implemented for each windfarm. The plan should be based on data collected during the pre-construction EIA as a baseline and must as a minimum define the species of greatest conservation concern. Furthermore, the plan must describe the threshold effects above which mitigating measures must be initiated. It is important that funding is committed to conduct such post-construction studies and the monitoring and mitigation plan should be required as part of any issued permits. Provision for data sharing and for making these pre- and post-construction data publicly available is a very high priority and the basis for agreeing industry standards in data gathering, collation and storage.

In the following sections, the guidance is broken down into three major sections, considering specific measures, namely flight behaviour, collision rate and ultimately the cumulative impacts at the population level. The descriptions of flight behaviour and estimations of collision risk apply to the EIA process as well as forming essential elements of the pre- and post-construction monitoring programmes, so it has been logical to include elements of these monitoring mechanisms, even where these lay strictly outside the scope of EIAs. The measurement of collision rate is, by definition, only possible under post-construction monitoring. Cumulative impacts may be measurable post-construction, although are unlikely to be attributable to a particular wind farm construction. These need to be carefully considered as part of any EIA.

4.2 Measuring effects on flight behaviour

Ideal objective

To construct a frequency distribution of individual bird and flock trajectories (identified to species) in three-dimensional space through a defined corridor against which to compare identical frequency distributions through the same corridor post windfarm construction in a manner that accounts for variation in weather conditions.

General objectives and constraints

This element of data collation enables some prediction of the likely number of individual birds and flocks likely to be flying through the area where turbines are planned, providing a basis for the crudest level of impact assessment, assuming no avoidance behaviour at all. Its value to the EIA process is limited whilst knowledge of avoidance reactions is restricted, and therefore it is most valuable as a comparative tool to compare bird flight trajectories before and after construction of wind farms. In conjunction with the other methods considered, these pre- and post construction comparisons are most powerful in gathering data to populate collision risk model estimations considered below. At the most complex level, the general objectives would be to describe trajectories in three-dimensional space in order to compare the pre- and post construction states statistically in a manner that accounts for difference in weather conditions. The assessment must also take account of the effects of season, time of day, weather, bird behaviour and other factors which are known to affect bird flight behaviour.

It is presently easier to describe individual bird and flock trajectories (not always identifiable to species) in two dimensions using simple azimuth ship navigation radar (as long as a geo-stable platform or large ship is available to avoid sea clutter). This approach has the distinct advantage of describing linear pathways in a manner that enables frequency distributions to be constructed and compared with relatively simple statistics. In essence, this is all that is needed, for example, to demonstrate the nature and magnitude of flying birds taking avoidance action to fly around the edges of a windfarm post construction. Using simple approaches, it is also possible to quantify the frequency distributions of the mean distances (and their variances) from the outermost turbines at which such course corrections are taken. Such data are essential to the process of contributing to EIAs on a case by case basis and informing our ability to make more confident predictions in the future.

Two dimensional descriptions of trajectories fail to provide critical information on flight altitudes, since flying birds may climb to fly over turbines as well modify trajectories laterally to avoid collisions. Vertical mounted marine navigation radar can very adequately address this problem, and does not necessarily require a geo-stable platform, but this only describes the trajectory and height of birds through a narrow swathe of scanned airspace.

Methods

Radar observations of the bird migration routes should be performed day and night during pre-construction, construction and post-construction. The number of observation days can vary between programmes and sites but must be adjusted to the local migration volume, which by its nature can constrain data collection. In the Danish study at Nysted, two observation days (48 hours) per week during the spring and autumn migration periods were conducted (Kahlert et al. 2004). Data should be recorded by 15-minute periods for later incorporation of visual migration information or weather variables in the statistical analyses.

To support the collection of radar data, visual observations of species composition and flock size should be collected simultaneously and for as many of the flocks detected by the radar as possible. A spotting scope (minimum 25x) can be used to identify the species of bird flocks (for waterbirds up to a distance of 6 kilometres).

The compilation of spatial data on bird migration at long distance and during periods of poor visibility due to fog or darkness requires a ship-radar. Each echo on the radar monitor corresponds to a flock of birds in the study area, and the accumulation of such tracks defines the spatial migration pattern, which should be compiled both during day and night (defined by official local times of sunset and sunrise). The basic data requirement is for definition of the geographical position of flying objects (preferably in three-dimensional space), their migration speed and course. The distance from the observation tower to the periphery of the study area may have to vary with the type of radar used and the ability to position such a radar platform in relation to the planned wind turbines, but with a 25 kW ship-radar flocks of waterbirds can be detected and followed out to a distance of c. 12 kilometres.

Time of day, season and wind directions have been shown previously to have significant effects on the migration patterns in the study area (Kahlert et al. 2000, Desholm et al. 2001, Kahlert et al. 2002). In addition, the response pattern of birds to operating wind turbines is hypothesised to be affected by visibility. However, periods of perfect visibility rarely occur at most sites for protracted periods, so it may be necessary to gather sufficient data by compiling data from the monitoring programme over more than one season before it is possible to make reliable assessments under a realistic range of weather conditions.

In previous studies, lateral avoidance has been considered the most frequent bird response to established wind farms (Winkelman 1992). An alternative hypothesis would be that birds are attracted for example by illumination of wind turbines (for a review on the subject of illumination, see Lensink et al. 1999), a phenomenon that only relates to nocturnal migrants. It is also possible that gulls and cormorants will use the static turbine superstructure as a resting platform during both day and night, resulting in relatively high numbers of radar tracks of birds moving towards and into the windfarm. Therefore, studies of migration routes must be designed to detect attraction effects also.

Lateral avoidance response

Based on the main hypothesis that migratory birds show a lateral avoidance response to the windfarm, the following predictions are made:

1) A gradual and systematic deflection of the migration route will occur with significant changes in the flight direction close to the windfarm after the turbines have been erected;

2) The change in flight direction will occur closer to the windfarm at night and during periods of poor visibility than during daytime and periods with good visual conditions;

Based on the alternative hypothesis that migratory birds show a lateral attraction response to the windfarm the following prediction is made:

3) A gradual and systematic deflection towards the windfarm will occur with significant changes in the flight directions close to the windfarm area after the turbines have been erected.

Only a fraction of all the collated migration trajectories can be used in an analysis of the lateral change in migration routes as an avoidance response to the windfarm. These tracks can be extracted for the analysis in several objective ways and will always depend on the general migration pattern in the study area. In the Danish study (Kahlert et al. 2004), 15 transects were placed (in the GIS) in parallel with and east of the most easterly row of turbines, so the waterbird flocks migrating westward towards the windfarm would pass at least some of them. This selection of data ensures that the analysis focuses on bird flocks approaching and passing through the windfarm area

The 15 transects in the Danish study were positioned 0, 50, 100, 200, 300, 400, 500, 1,000, 1,500, 2,000, 2,500, 3,000, 4,000, 5,000 and 6,000 metres from the most easterly row of turbines, respectively, and had the same orientation and length as this row. Again the distances between the transects can be adjusted to fit a given study design and study area. For each track a migration course must be calculated for each interval between two adjacent transects, as the course between the intersections of the migration track and the two adjacent transects. For each transect interval the mean migration course and its standard deviation of the recorded tracks must be calculated.

The mapping of migration routes gives the opportunity to test potential changes in the mean orientation at different distances from the windfarm area, and to test whether a systematic change in migration route has occurred. For example, if most birds avoid the windfarm by making lateral adjustments to the north, the mean track orientation post construction will differ as a result of this lateral reorientation. If data from all sectors are normally distributed and show equal variance, the differences in the mean course at a specific distance can be tested using a t-test after establishment of the windfarm. However, if birds show lateral response differences in the distributions of migration courses with respect to distance to the wind turbines, e.g. a deflection of individuals both to the north and to the south of the wind turbines, this could result in a bimodal distribution close to the windfarm, but a unimodal distribution further away where the deflection has not yet begun. In this case, one could expect no significant difference in mean orientation, but a significant increase in the standard deviation of the mean.

Northerly and southerly winds can displace westward-migrating flocks to the south and north, respectively. Time of day (day and night) may affect the spatial placement of migration routes, especially after the wind turbines have been erected (*cf.* predictions from the hypothesis). The effects of wind direction, time of day, distance to the windfarm and year on the orientation of migration can be tested using repeated measures ANOVA.

Reverse migration, which may be a relevant factor in the case of a severe response from the birds to the windfarm, can be studied by daytime spotting scope observations. These observations include recordings of species, number of birds and flock size, and must be carried out simultaneously with radar observations to derive species specific data on the migration patterns through the study area. The observations by spotting scope can be undertaken along a transect which cover the main migration approach routes towards the windfarm. For each observation it was noted whether the birds were flying towards or away from the windfarm, and hence, the proportion of the flocks flying away from the windfarm can be computed on the species level.

Probability of passing the windfarm

In relation to the main hypothesis, that migratory birds show a lateral avoidance response to the windfarm, it can be further hypothesised that the probability of passing the windfarm area after erection of turbines will decrease.

Again an objective way of extracting the tracks for this analysis must be designed. Which tracks must be dealt with and what are the conditions that tracks must meet in order to be classified as either entering or not-entering the windfarm?

Flocks (radar echoes) must be followed to see whether they cross the windfarm area or not, and the proportion of flocks that actually do so must be calculated.

In order to describe the migration pattern in detail, logistic regression models can be used to describe the probability of passing the windfarm area incorporating the following factors:

- position and direction of the track
- time of day (i.e. day and night),
- wind (e.g. north-, west-, east or southerly winds),

- precipitation,
- season, and
- year

Finally, modelling the frequency of meteorological events that are found to predispose birds to increased collision risk in a given proposed wind farm area, using meteorological data from a nearby site, would be helpful in assessing risk.

4.3 Local collision rates

4.3.1. Constructing collision probability models

When constructing collision prediction models we have to discern between models for EIA studies (pre-construction) and models for effect studies (pre- and post-construction) since only the latter offer the opportunity of including the avian evasive actions towards wind turbines. This is because current data on species-specific evasive manoeuvring is very scarce. Consequently, such data on evasive manoeuvre capabilities need to be collected at the study site of interest before proper estimates of the number of collisions (including avoidance behaviour) can be estimated through quantitative predictive modelling. Nevertheless, it is recommended to build models based upon non-evasive action (on the part of birds) as part of the EIA studies as a first crude assessment of the potential risk of collision for any proposed windfarm.

Ideal objective

To estimate a hierarchy of probabilities that a given bird in a flock at a given distance from the windfarm on a given trajectory will collide with any of the turbines in a windfarm given a range of weather conditions.

General objectives and constraints

This element of data collation is in essence the same as that above. It requires data that enables some prediction of the likely number of individual birds and flocks flying through the area where turbines are planned, providing a basis for the crudest level of impact assessment, assuming no avoidance behavior at all. However, with increasing experience from other projects, it becomes possible to assign probabilities to the likely numbers of birds that actually enter wind farms based on before-after comparisons, to assess their ability within the wind farms to avoid flying in the vicinity of the turbines and ultimately the likely probability of collisions amongst the residue that approach the blade sweep area and superstructure, accounting for observed rates of last minute avoidance reactions. These avoidance probabilities will most likely be species specific and are also affected by changes in weather conditions, which also need to be considered when constructing models.

Three-dimensional descriptions of the flight trajectories are again the ideal objective. However, in reality, it is presently easier to describe individual bird and flock trajectories (not always identifiable to species) in two dimensions using simple azimuth ship navigation radar (as long as a geo-stable platform is available to avoid sea clutter). This approach has the distinct advantage of describing linear pathways in a manner that enables frequency distributions to be constructed and compared with relatively simple statistics. In essence, this is all that is needed, for example, to demonstrate the nature and magnitude of flying birds taking avoidance action to fly within the windfarm, but well away from individual turbines. Using simple approaches, it is also possible to quantify the frequency distributions of the mean distances (and their variances) flying birds maintain from adjacent turbines. Again, such data are essential to the process of contributing to EIAs on a case by case basis and enhance our ability to make more confident predictions in the future.

Two-dimensional descriptions of trajectories fail to provide critical information on heights, since flying birds may climb to fly over turbines as well as modify trajectories laterally to avoid collisions. Both TADS (which requires a geo-stable platform) and vertical mounted marine navigation radar can very adequately address this problem (which does not necessarily require a geo-stable platform). Data gathered using these techniques, can be effective at describing the trajectories and height of birds through a narrow swathe of scanned airspace.

Framework for a collision model

Risk of collision is defined as the proportion of birds/flocks exposing themselves to a collision by crossing a collision conflict window (e.g. windfarm or area swept by the rotor-blades). The risk of collision (r_i) is assessed at four levels of conflict windows: Level 1 relates to the study area, level 2 the windfarm, level 3 the horizontal reach of rotor-blades, and level 4 the vertical reach of rotor-blade (Fig. 4.3.1). The value of r_i can be measured directly for each level post-construction as the transition probability distribution, or be estimated pre-construction by multiplying the pre-construction proportion of birds/flocks (p_i) passing the level specific conflict window with the assumed (published estimates) proportion of birds (a_i) not showing any evasive behaviour at the given level. After level 4, a factor describing the by-chance-probability (c) of not colliding with the rotor-blades must be incorporated to account for those birds safely passing the area swept by the rotor-blades by chance (Fig. 4.3.1; Tucker 1996, Band et al. in press). An overall risk of collision (R) can be obtained by multiplying the four probability risk values:

$$R = r_1 \times r_2 \times r_3 \times (r_4 \times (1-c)) \qquad \text{Equation 1}$$

The simple deterministic way of estimating the overall number of collisions at the windfarm ($n_{collision}$) would be to multiply R with n_1 using mean values for transition probabilities and for the c-value. The more profound way of estimating $n_{collision}$ would be by simulating the migration event from n_1 through $n_{collision}$ in accordance to the collision prediction model (see Fig. 4.3.1) by resampling transition probabilities from field data-based probability distributions and applying the re-crossing loop (flocks passing more than one turbine during their windfarm crossing; Fig. 4.3.1).

This model can be applied for different scenarios:

- day and night,
- tail-, head- and cross-wind (especially r_3 and c is affected by wind direction), and
- rotor-blades, foundation and turbine tower.

Finally, the results from these partial models can be combined in an overall estimate of the number of collisions at the windfarm under study. Parameterisation of the collision prediction model can be done by applying a combination of radar, TADS and visual observations in the data collection protocol as follows for each of the four spatial levels (Fig. 4.3.1):

Level 1. This level relates to the study area and specifies its in-crossing number n_1 representing the overall number of birds/flocks passing the study area during a migration event (i.e. spring or autumn migration season).

Level 2. For this part of the analysis radar data defining the probability distribution/proportion of migrants passing the windfarm is needed (r_1).

Level 3. For this part of the analysis radar data defining the distance to nearest turbine is needed for those flocks that pass through the windfarm. From the compiled frequency distribution of distance to nearest turbine, the proportion (r_2) of the migrating flocks that pass within the risk horizontal distance (equals the length of the rotor-blades) of the turbines can be calculated for day and night. Desholm (2005) has recently recorded such diurnal difference in mean distance to turbines for waterbirds

Level 4. In order to estimate the proportion (r_3) of birds flying within the vertical reach of rotor-blades, a height distribution is needed. Depending on the level of information on migration altitudes the height distribution can be either based on theoretical calculations or more preferable on directly measured altitude data collected at the study site. Altitude data on migrating birds can be collected by operating a surveillance radar vertically or by applying the height data collection protocol by TADS (Desholm 2005).

At this stage n_4 (number of birds/flocks passing the area swept by the rotor-blades) is estimated and the final transitions to birds colliding ($r_4 \times (1-c)$) and avoiding the rotor-blades ($e_4 + (r_4 \times c)$) must hereafter be executed. For inclusion of the near rotor-blade evasive actions (e_4) which must be collected during both day and night, infrared detection systems (e.g. TADS) must be applied to collect data on ability of the different species of birds to perform evasive actions when crossing the sweeping rotor-blades. So far, such evasive factors have only been reported in the study by Winkelman (1992) using a thermal camera. Finally, an avoidance-by-chance factor (c) must be implemented after level 4 for those birds crossing the area swept by the rotor-blades safely without performing any evasive actions. Procedures for calculation of “c” can be found below and in Tucker (1996) and Band et al. (in press) and be directly incorporated in the collision prediction model.

The end product of the collision prediction model will be the predicted number of birds colliding with the turbines:

$n_{collision} = n_4 \times r_4 \times (1-c)$ Equation 2

and the predicted number of birds that avoid (either by chance or by evasive actions) colliding with the turbines:

$n_{avoiding} = (n_4 \times r_4 \times c) + \sum(n_i \times e_i)$ Equation 3

where n_1 (overall number of birds passing the study area) equals the product of . $n_{collision}$ and $n_{avoiding}$.

The Tucker model

In general, this collision model describes the probability of collision depending on the motions and dimensions of the bird and the blades. A collision is defined as the event when a bird and a rotor blade occupy the same region in space and time. Different models are presented for different wind situations in relation to the flying birds (head, tail and cross wind) and for one-dimensional and three-dimensional blades. Tucker (1996) shows that the collision probabilities vary over the surface of the disk swept by the blades, and in most cases, the tip of the blade is less likely to collide with a bird than parts of the blade nearer the hub. The paper by Tucker (1996), also present a more applicable measure of the mean probability of a collision which is calculated as the spatial average of the probabilities over the surface of the disk. It is concluded, that the mean probability averaged over the surface of the disk is lower for downwind flight than (0.191) for upwind (0.335) or crosswind flight (0.472 – 0.535), and that the mean probability calculated from the simpler model of one-dimensional blades should be sufficiently accurate for many purposes.

In the following is the simple model of one-dimensional blades and the downwind situation described as the mean probability of a collision:

$$\bar{p} = \frac{Bb}{2\pi}\left(\frac{\Omega}{A\left|V_{bx} + (1-a)U\right|} + \frac{4}{\pi\left(R + \frac{V_0}{\Omega}\right)} \right) \qquad (1)$$

where B is number of blades in the rotor, b is wind span of bird (m), ☚ is angular speed of the blades (radians/s), A is aspect ratio of bird, V_{bx} is component of bird velocity relative to air (m/s), a is axial induction factor, U is wind speed relative to ground (m/s), R is radius of rotor disk (m), and v_0 is tangential threshold speed of blade (m/s). See Tucker (1996) for further detail on the construction of the model and its variables.

The Band et al. model

In general, this collision model can be used to estimate the number of bird collisions over a period of time and includes both the stage of estimating the volume of birds

passing the sweeping area and the stage of calculating the probability of collision for birds passing the area swept by the rotor blades. In this context the latter stage of collision probability will be presented and discussed.
The probability of collision is calculated on the basis of the size of the bird (both length and wingspan), the breadth and pitch of the turbine blades, the rotation speed of the turbine, and the flight speed of the bird. An Excel spreadsheet is available on the Internet that makes this model easy accessible and easy to use (bill.band@snh.gov.uk or phil.whitfield@snh.gov.uk).

In the following is the simple model of one-dimensional blades and the downwind situation described as the probability p of collision for a bird at a radius r from hub:

$$p(r) = \frac{b\Omega}{2\pi v} \times \left[\left| \pm c \sin\gamma + \alpha c \cos\gamma \right| + A \right] \qquad (2)$$

Where b is number of blades in rotor, ☚ is angular velocity of rotor (radians/sec), v is velocity of bird through rotor, c is chord width of blade, ☟ is pitch angle of blade, 👆 is v/r☚ and A is 1 if 👆<☝ or w👆F if 👆>☝, w is wingspan of bird, and F is 1 for birds with flapping wings. The Excel spreadsheet offer the an estimate of the overall p(collision) for head and tail wind where a numerical integration from r = 0 to r = R is undertaken; where r is radius of point of passage of bird and R is outer rotor radius.

It is beyond the scope of this report to evaluate and compare the two theoretic models of collision probability for no-avoidance sweep area passage by flying birds. In general, it can be concluded that both models present theoretical estimates, that due to the intentional lack of an avoidance factor, will assess the relative potential collision risk for different bird species that takes no account of any avoidance response on the part of the birds.

4.3.2. Measuring actual collision rates

Ideal objective

The ideal objective is to count and identify to species the number of birds striking the turbine superstructure throughout an entire windfarm over a given period. This includes the numbers of birds mortally injured when caught in air turbulence vortices associated with the turbines. Given a relationship with particular weather/visibility conditions, a secondary ideal objective would be to determine conditions under which collisions are most frequent.

General objectives and constraints

Remote sensing technology is necessary since it is not possible to recover bodies of birds killed by collisions at sea. Currents and scavengers conspire to remove corpses from the vicinity of turbines, so some means of monitoring is necessary. The TADS approach has the advantage of being effective at night and offering (through information on body shape, flock structure, wing beat frequency and other features) the opportunity to identify birds to species or species groups. TADS also enables retrospective analysis of the effects of factors such as weather and visibility on collision rates. Most other techniques currently fail to do this, but the technique offers restricted spatial coverage at present.

Methods

The hardware to be used in a collision monitoring study with TADS has been described earlier. The TADS is constrained by its relatively low optical resolution and high costs, and hence, the amount of data that can be collected at single site may be limited if resources are limited. Consequently, it is important that experiences from different collision monitoring studies can be compiled into a library of data, so enough information on species-specific risk of collision can be collected over a longer period of time. The objectives of future collision monitoring TADS-studies aims at answering the following questions: What is the species-specific probability of collision for birds approaching the turbines, and is the probability related to weather conditions, flight speed, flight altitude or flock size?

The camera must be mounted on the side of the turbine tower from which the migration comes from. Data must be collected as continuously as possible during both day and night during the migration period. One operator can perform all the camera adjustment settings and data collection, but it is preferable to have two people for greater flexibility and higher monitoring efficiency.

Three different views can used during data collection:

View 1) the preferred vertical view for monitoring the birds passing or colliding with the turbine tower and the turbine blades,
View 2) the 45° angle view for monitoring the bird behavior in the near vicinity of the turbine,
View 3) the horizontal view of the neighbour turbine.

View 1 is the view used for detecting avian collisions. Because the housing that supports the TADS is fixed in one position on the tower, this view is restricted to one orientation. It is positioned on the side of the turbine likely to experience the most collisions (i.e. the side from which most birds approach). This view is only operated when the wind comes from the opposing direction (i.e. in westerly winds if the TADS is mounted on the eastern side of the turbine tower). View 2 and view 3 offer the secondary viewing for collecting data on flock size and flight altitude, and should be used only when collision monitoring is not an option due to unfavourable wind directions.

In cases where the automatic monitoring in the vertical mode of the sweep area fails to detect birds in the field of view, a control-monitoring scheme using manual recordings in horizontal mode can be set up, in order to verify that e.g. the lack of detected birds is caused because the birds are migrating in between the turbines just above sea level.

From the recorded thermal video sequences, the following data must be derived and collected for further analysis:

- species specific number of birds colliding or passing the turbine or passing in the near vicinity of it,
- number of sequences triggered and recorded,
- sequence length (seconds) for estimating the monitoring efficiency,
- view type,
- wind conditions during data collection,
- visibility during data collection,
- numbers of and reasons for the non-bird triggered sequences (when other objects than birds triggered the recording; see below).

In the Danish study (Desholm 2005), a single operator managed an operation efficiency of 74% which corresponds to the percentage of time during the whole migration period when the TADS ran successfully. This meant that out of a study period of 27 days during the spring migration period of 2004, the TADS was operational for 20 days.

However, in addition to flying birds passing the field of view that will be recorded by the TADS some non-bird sequences will also be captured. These non-bird triggered sequences can be caused by (i) the appearance of the rotor-blades within the field of view as a result of a change in wind direction, (ii) changing temperature patterns in the background of the camera view due to solar heating of the atmosphere, or (iii) relatively warm drifting clouds. During the 20 days of TADS operation in the Danish study (Desholm 2005), 1,200 non-bird sequences were triggered by the trigger software. However, such sequences were easily identified as being non-bird sequences and could be processed and removed within a few minutes in a single operation, and these periods were then excluded from the monitoring time. Consequently, the monitoring efficiency was ultimately 64% (percentage of time when the TADS was ready to detect collisions excluding the periods where wind direction or temperature pattern changed unexpectedly).

The following describes the daily operator protocol for a TADS monitoring program:

1) Before the migration volume peaks in the morning the operator must log on to the system computer at the turbine tower for adjusting the camera settings for the present weather conditions. The recorded thermal video sequences of the previous night are scanned through over the Internet link to detect and delete the non-bird-triggered sequences. Start and end time is always noted when logged on the system so the monitoring time at the end of the season can be calculated.

2) Around midday, the procedure described under 1 is repeated and the sequences are transferred to the hard disk at the office and deleted from the tower computer. A back-up copy of all the sequences of interest is always saved.

3) In the evening the procedure described under 1 is repeated again.

The number of camera setting events depends on the variability of the present weather conditions, and the protocol described above referred to a day with stable conditions whereas a day with continuously changing wind direction and/or precipitation levels may need up to ten camera setting events.

When designing a TADS monitoring programme aiming at measuring the avian collisions directly, the level of collision effect must be taken into account. TADS can be used for either a high intensity programme for measuring the low daily collision frequency or for a low intensity programme for detecting periods with high numbers of collision casualties under rare and unusual situations. Such mass casualty events have been reported in studies of illuminated land-based super-structures (Lensink et al. 1999, Nilsson & Green 2002), and may occur at offshore wind farms as well under conditions where either the weather, factors that attract birds (e.g. light or food) or some other factors or a combination of factors result in high collision events.

4.4 Impacts on the population level

This report deals exclusively with the local effects from single wind farms, but more interesting in a biological and ecological perspective is the impact on the population level of the bird species involved. A fly-way population of a specific species may not be impacted by eighty 2 MW turbines erected at a single site, but if we are dealing with a long-distance migratory bird species, these might have passed several other utility structures along their migratory corridor. Thus, from a conservation management perspective all the potential local effects must also be assessed in a cumulative context. Such population level assessments can not be expected to be dealt with at every single windfarm, but must be handled at a more strategic level, perhaps co-ordinated by governmental institutions. However, if threshold levels of local negative effects are being produced, on the basis of more strategic population assessments, protocols and governments must provide best practice guidance for local EIAs. However, since avian migrants, by their very nature, cross national boundaries, a forum like the EU might be a suitable level for developing such strategic guidelines.

5. RECOMMENDATIONS FOR FURTHER METHODOLOGICAL DEVELOPMENT

The wind industry is in its initial stage of exploiting the European offshore waters, and hence, very few EIAs on wind farms have so far been conducted in offshore areas. As a consequence, only a limited amount of experience has been gained about the use of radar and TADS technologies in this specific context. Some promising methods are still to be developed and some of the existing technologies could benefit from a further development or bird-turbine specific adjustments. The integrated use of several of the described remote technologies is still in the development stage, e.g. the combination of vertical parabolic disc radar and thermal camera. This section will highlight the challenges of the future development possibilities and try to rank these in terms of importance (i.e. their gap filling properties).

5.1 Radar

So far information has been published on the results obtained only from the use of horizontal surveillance radars in studies of offshore wind farms (Christensen et al. 2004, Desholm et al. 2003, Kahlert et al. 2002, Kahlert et al. 2004). Hence, although the combined set-up of both a vertical and horizontal radar is being used and developed, they cannot be currently co-ordinated in a way that is helpful to gather combined data on bird flight movements. Hence, the full potential of using both approaches still needs to be tested in an offshore windfarm context. Other limitations of current radars include:

- Poor range performance and poor range resolution
- Serious limitations in rain and problems with returns from sea clutter
- Current avian labs are too bulky for low cost offshore mounting
- Very poor species identification
- Incompatibility of calibration procedures between different radars

The development of a high specification bird radar to address all of these limitations could start immediately, subject to availability of funding (estimated £200,000 to £500,000 depending on specification).

5.2 Collision models

First of all, the avoidance behaviour needs to be incorporated in the models since this factor is obviously very important, but nevertheless, this has so far not been incorporated in the collision risk assessments in relation to wind farms. Specifically, the avoidance behaviour must be incorporated in the model set-up of the combined no-avoidance collision models and the probability models. Furthermore, verification of models through the use of carcass collection (at land based wind farms) and/or TADS is of absolute importance in the immediate future. It is essential that such model validation be performed so that an assessment of their accuracy can be presented in the EIAs, well in advance of construction of the future wind farms. The overall aim must be to attain the possibility of conducting pre-construction risk assessments, both on the local and population level, and well in advance of the erection of turbines.

It could also be of great value to perform some sensitivity analyses of the no-avoidance collision models to assess the relative importance of the different factors. How much does the angle of attack alter the risk of collision compared to e.g. the effect of avoidance? Such questions and their answers would help us to focus on the most parsimonious models and to make the collision risk assessment as cost effective as possible.

5.3 Measuring actual collision rates

5.3.1 TADS

It could be of great value to perform terrestrial validation tests of the TADS, so that the collision measures from this remote technology could be verified by carcass collection on the ground. This approach to verification is clearly impossible in association with offshore wind turbines. The amount of data generated from TADS monitoring is still very limited, and hence, further collection of data could enhance our understanding of this passive infrared technique and its application possibilities in the future. Finally, the trigger software could be further refined and made even more effective, e.g. by adding a dynamic and automated camera setting component which would reduce the number of times per day the operator must log on to the camera computer. The monitoring efficiency could be further increased if an automated mounting device could be developed that could follow the movements of the nacelle, around the turbine tower, with the changing wind directions. In this way, a single TADS could cover all possible wind directions and consequently be monitoring for collisions every day during the migration period.

5.3.2 Others (microphones, sensors, etc.)

Another possibility could be the development of a low cost sensor-system for detecting the impact from bird-turbine collisions for large-scale implementation, i.e. at every turbine in a windfarm. It could be either a further development of the WT-bird microphone system (Verhoef et al. 2004). Alternatively, it could be based upon a system using the piezo-electric technology that can detect acoustic vibrations or other signals in materials (e.g. vibration waves arising from the impact of birds hitting the rotor-blades, nacelle or tower construction). Presently, such a piezo-electric sensor project is only in the planning process but hopefully funding can be raised to develop such a programme.

6. RECOMMENDATIONS

6.1 Radar

The strong recommendations emerging from the Workshop held at Malvern were that radar was a very powerful tool for generating data that could support the EIA process. This is particularly the case with regard to assessments of the level of bird traffic in the vicinity of a proposed wind farm, the degree of avian avoidance of wind turbines once these were constructed and the costs (extra flight distances) and benefits (reduced collision risks) of these avoidance behaviours. Basic marine surveillance radars offer very cheap utility and were considered a very suitable option for gathering such data. More expensive dedicated bird detection radar (e.g. the avian labs) allows more sophisticated analysis using spatial modelling techniques in a GIS platform. The Workshop also concluded that because so little data existed at the present time upon which to base EIAs, it was essential that standard protocols were put forward to ensure uniformity of data collection. Fundamental to providing a sound baseline is that data are collected in a comparable way, enabling comparisons between different seasons at the same site and between sites. However, it was difficult to see how, using surveillance radar of the form commonly utilised for these types of project, this might be achieved, especially given different groups using different forms of radar equipment and the associated corrections needed for detectability, repeated calibration and standardisation of settings.

For this reason, a summary overview of the broad aims of how radar may contribute to the assessment of bird migration and general flight movements as part of an EIA can be found in Table 6.1.1. However, it is difficult at this stage to offer highly specific guidance on the data that need to be collected from such investigations and how these should be presented. Nevertheless, as experience is accumulated and the field expands, it will become increasingly possible to specify data form and quality. Hence hopefully, these issues will be dealt with in more depth in later iterations of this reporting round.

6.2 TADS

The view of the workshop was an acceptance that TADS was the most promising technology for measuring collision risks available at the present time. Any lack of greater enthusiasm for the application of this method was due to its high price and the limited field of view, because there is an inevitable trade-off between image definition and the width of the field of view. That said, it was agreed that TADS remains the only technology available that can successfully capture imagery of flying birds in close proximity to turbine blades by day and night, even during conditions of heavy precipitation and poor visibility. The existing equipment has generated imagery that enables interpretation of detailed avoidance reactions shown by passerines and has been used to great advantage to measure species-specific flight heights and flocks sizes at night, which is currently impossible to obtain by other methods. In terms of expense, the equipment available can only become cheaper in the immediate future as the imaging technology improves and the market expands. It was the view of the meeting that the combination of vertically mounted radar and infra-red imagery equipment mounted in close proximity to the turbines had the added advantage of generating data on flight trajectories and height which necessitated further research and development, but showed considerable promise.

6.3 Other potential observation models

It was generally accepted by the meeting that most other forms of remote sensing technology suitable for tackling the issues facing developers in the development of offshore wind farm EIAs were still in the research and development stage. Some (such as the remote video surveillance technology and the sound/vision collision monitor of ECN) were being tested at the time of the workshop and the community therefore awaits the results of these and further trials. It was acknowledged that some of the methods would never provide fully adequate data (e.g. because of shortcomings such as laser range finding being applicable only by day and moon–watching being restricted to clear nights with a moon), but could supplement more robust methods with useful data. Other methods, such as the use of ceilometers, could provide supplementary data, but with serious caveats relating to the data. It was also acknowledged that those technologies that still promised some prospect of providing necessary data (but which are largely inaccessible using existing methods) would be worth appropriate R&D investment. In particular, it was noted that whilst radar provided valuable spatial data on bird flights, no amount of development would enable its use to collect data on near-turbine avoidance behaviour and collision rates. Equally, while the TADS provided excellent data on species specific near-field avoidance behaviour, collision risk and flight heights, it was acknowledged this was expensive and had other limitations. The overall conclusion of the workshop was that we still lack a cheap and robust means of measurement of collision rates at offshore wind farms that would better quantify this measure by generating extensive data based on large sample sizes from many situations. The measure of this rate is so essential to the formulation of informative EIAs, and it was in this area that the Workshop agreed more research investment should be placed in the future.

Table 6.1.1. Overview summary of the objectives for radar assessment of migration and other bird flight movements in the vicinity of a proposed windfarm project area (after BSH 2003)

	Baseline surveys Preliminary investigations	**Baseline surveys Assessment**	**Monitoring construction phase**	**Monitoring operational phase**
TARGETS	Assess the seasonal extent and nature of avian flying activity within the proposed windfarm area	Define the volume and seasonal variation in avian flight traffic within and around the proposed windfarm area	Observe and quantify the degree of change in the seasonal extent and nature of avian flying activity within the windfarm area during construction	Observe and quantify the degree of change in the seasonal extent and nature of avian flying activity within the windfarm area post construction
MINIMUM OBJECTIVES	To determine the level of migration, diurnal displacement and local feeding flights, as well as regular movements between foraging, nesting and resting grounds	To assess the degree of within and between season and year variability of these movements	To record the level of change in bird traffic resulting from construction activities, especially with respect to avoidance behaviour at various spatial scales	To record the level of change in bird traffic resulting from the construction of the windfarm, especially with respect to avoidance behaviour at various spatial scales
MINIMUM RECOMMENDED EFFORT	Sampling regime should aim to cover at very least 7 full days (24 hour coverage) per month, in the peak periods (preferably not in a single block). This should cover the main migration periods (March-May and mid-July-November inclusive), the breeding season (May-July inclusive) and wintering period (November-March inclusive) where these are known to be relevant to the species present from initial surveys and screening. At least 25 days per year should be achieved to ensure sampling of variability Baseline surveys should cover a minimum of 2 (preferably 3) annual cycles to achieve maximum quantification of inter annual variability, both during the baseline and post construction phases (although the brief duration of the construction phase offers no such opportunity)			
SPECIFIC OBJECTIVES	Accumulation of a baseline, sampling track intensity approaching and entering the site of the proposed windfarm		Accumulation of post construction data to demonstrate the reactions of flying birds to the presence of the windfarm post construction in terms of changes in flight direction/altitude to compare with the baseline	
METHODS				
Locations	Geo-stationary locations, alternatively on vessels, positioned in the direction from which the greatest number of birds approach the windfarm site to ensure optimal detection of avoidance behaviour			
Vertical radar objectives	Quantify flight intensity at different altitudes relative to the proposed wind turbine heights Quantify seasonal variation in flight intensities			
Horizontal radar objective	Quantify flight intensity in cross-sectional 2 dimensional space relative to the windfarm Quantify seasonal variation in flight intensities Quantify the variation in flight direction			
Vertical and horizontal radar specifications	Vertically mounted marine navigation x-band radar at least 10 kW, vertical beam width 20°-25° horizontal bean width 0.9°-1.2°, regular operational range 1-2 nautical miles Horizontally scanning marine navigation radar at least 25 kW, regular operational range 1-6 nautical miles			
Presentation of results	Summarisation of all pre, during and post-construction trajectories and intensities Comparison of before, during after construction distributions			

7. ACKNOWLEDGEMENTS

The authors are extremely grateful to the COWRIE consortium for funding to produce this report and to gather interested parties to the workshop held at the Malvern Technology Centre in April 2005. We would especially like to thank Rowena Langston of the RSPB and contact point for the COWRIE consortium for her help and support above the call of normal duty. We are extremely grateful to Carolyn Heeps and Cathryn Hooper at the Crown Estate for their help, advice and support throughout. We wish to sincerely thank all the external experts that have improved on earlier versions of this manuscript and those of them which took active part in the workshop in the UK. We thank our respective organisations (the Department of Wildlife Ecology and Biodiversity of the Danish National Environmental Research Institute (TF and MD) and QinetiQ (PB)) for providing their support and backing throughout the course of this project. We thank Ian Locker, Andrew Beck and James McQuillan at QinetiQ for their support of the project, Dr Simon Bennett (MD Technology and Products QinetiQ) for opening the workshop and Johnny Kahlert and Birgit Laugesen (NERI) for their help and support. We thank our many colleagues at NERI for their help, support and experiences that have helped shape this report, especially Johnny Kahlert, Thomas Kjær Christensen, Ib Krag Petersen, Ib Clausager, Henning Noer and Karsten Laursen.

We are extremely grateful to all of the participants at the workshop hosted by QinetiQ at their Malvern site in April 2005. Everyone attending the meeting gave freely of their own experiences and we are very grateful for their contributions. We are especially grateful to Sidney Gauthreaux (Clemson University, South Carolina, USA), Sjoerd Dirksen (Bureau Waardenburg, the Netherlands), Felix Liechti (Swiss Ornithological Institute, Sempach) and Ommo Hüppop (Vogelwarte Helgoland, Germany) for their stimulating presentations and for sharing their extensive experience at the workshop. We also thank Addy Borst (TNO Netherlands), Richard Walls (Central Science Laboratories, York, UK) and Peter Barlow (Outersight, UK) for their submissions and contributions to the Workshop. Many participants provided verbal comments and observation on the report which are gratefully acknowledged. We especially thank Bruno Bruderer, Sjoerd Dirksen, Jeremy Hatch, Rowena Langston, Dieter Todeskino and Richard Walls who took the trouble to provide detailed written comments to the original document mounted on the Web, for which we are extremely grateful.

Finally (with humble apologies to anyone we may have forgotten) we thank the conference centre staff (especially Karen Wheatstone) at the Malvern site for their hospitality and the faultless organisation of the workshop.

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9. APPENDICES

Appendix 9.1 Frequency Licensing Requirements

The co-ordination of global telecommunications is carried about by the International Telecommunications Union (ITU), an organisation within the United Nations System. The ITU maintain the International Table of Radio Regulations, which is amended whenever necessary to accord with any changes made by the World Radiocommunications Conferences. The International Table is grouped into three geographical World regions. Europe and Africa are in Region 1. The Table provides allocations of radio services up to 275GHz and prioritises these into primary and secondary. Typically, secondary services can operate only if they do not interfere with primary services. Radar is covered by two services defined as follows:

1. Radionavigation – Radiodetermination used for the purposes of navigation including obstruction warning.
2. Radiolocation – Radiodetermination used for purposes other than radionavigation.

Bird detection radar is classed as ‘radiolocation’.

In the UK, the Office of Communications (OFCOM) regulates the radio spectrum. OFCOM produce the UK Table which takes the recommendations from the International Table and refines it for UK military, government, commercial and domestic requirements see:

http://www.ofcom.org.uk/licensing_numbering/radiocomms/ukfat/fat2004.pdf

With the exception of some licence-exempt services, every piece of radio-communications equipment requires a licence. These licences fall into three different types:

1. Pre-packaged – an ‘off the shelf’ licence that mostly requires no specific assignment or co-ordination.
2. Customised – a licence that is ‘hand crafted’ to specific needs
3. Spectrum – This authorises the use of a whole block of spectrum.

Most bird detection radar will require a customised licence.

Inspection of the UK Table indicates the frequency bands that may be suitable for operating a bird detection radar either on land, or at sea, see Table 9.1.1. Note that services in upper case are primary, those in lower case are secondary.

Frequency in GHz	Radar Band	Service	Comments
2.900 – 3.100	S	RADIOLOCATION RADIONAVIGATION Radiolocation	Radiolocation requires co-ordination with MoD. Radionavigation not affected.
9.320 – 9.500	X	RADIONAVIGATION Radiolocation	Maritime radionavigation is for shipborne radars
15.70-17.30	Ku	RADIOLOCATION	*
33.4 – 36.0	Ka	RADIOLOCATION	*
59.0 – 64.0	U	RADIOLOCATION	Responsibility for assignment is by MoD
76.0 – 78.0	W	RADIOLOCATION	Responsibility for assignment is by OFCOM
92.0 – 95.0	W	RADIOLOCATION	Responsibility for assignment is by MoD

Table 9.1.1. United Kingdom frequency bands that may be available for bird detection radar. *Except by special agreement having the approval of the National Frequency Planning Group this frequency band, or the allocation to this service, is reserved exclusively for MILITARY use.

Table 9.1.1 shows that there is potentially a large spread of frequencies available. The S and X band radionavigation service is used for marine navigation radar from small boats to large ocean-going vessels. These types of radar start at prices of about £500, which is the main reason why they are the most commonly used radar for bird detection, which is, strictly speaking, a form of radiolocation. These radars operate using a ‘pre-packaged’ licence as radionavigation radars. However, when they are used for radiolocation from a fixed installation, either on land or at sea, it is necessary to apply for a custom licence. For ship-mounted systems the user can justify that it is being operated for radionavigation and using it for bird detection is a secondary benefit!

The Ku and Ka bands are currently used almost exclusively for military radars. To use these bands it would be necessary to present a case to the National Frequency Assignment Panel almost certainly using the DTI to lobby the case.

At U band and the higher frequency assignment of W band, radar activity is sparse and the MoD is responsible for frequency assignment.

At the lower frequency assignment of W band, OFCOM is responsible for frequency assignment for civil radiolocation, which includes radars, mounted on automobiles for collision avoidance and cruise control.

In the UK, OFCOM has provision for allocating temporary Test and Development (T&D) licenses. These are ‘made to measure’, and are allocated on an *ad hoc* basis depending on the research and development needs of the customer. Users of temporary licences have no protection from interference, and licences are granted on a non-interference basis, so that they if they cause interference to other users, they must cease transmitting immediately. The licences are granted on the understanding that they must not be used for operational purposes, and granting a T&D licence does not represent an expression of intent by OFCOM to issue operational licences on that frequency.

Given that the use of bird detection radar for Environmental Impact Assessment typically is carried out over short intervals of time and is still very much a research activity, application for a T&D licence is the recommended route. Also a T&D licence is much more likely to be granted for the MoD controlled bands than an operational licence.

The licensing regulations not only govern the RF centre frequency at which a radar can operate but also the bandwidth over which they can be modulated. The RF modulation bandwidth is inversely proportional to the range resolution of the radar. The ability to minimise range resolution helps to discriminate between individual birds, reduces the masking effect of rain and sea clutter and can, generally, improve the sensitivity of the radar. Available bandwidth increases with increasing frequency and so range resolution improves with increasing frequency.

Appendix 9.2 A comparison of performance calculations for two marine navigation radars

The following equation has been used to estimate the bird detection performance of two typical marine navigation radars. The Furuno 2125 is a 25kW X band radar and the Furuno 2165 is a 60kW S band radar. The performance for each radar is estimated for one of the short pulse settings and one of the long pulse settings.

$$R^4 = \frac{P_{av} t_0 G_t G_r \lambda^2 \sigma}{(4\pi)^3 k T_s SNR L_t L_\alpha L_{bs} L_m}$$

Where;

R	is the target range (m)
P_{av}	is the average transmit power (W)
t_0	is the pulse repetition interval (s)
G_t	is the transmit antenna gain
G_r	is the receive antenna gain
λ	is the wavelength (m)
σ	is the radar cross section (m^2)
k	is Boltzmann's constant (1.38×10^{-23} J/K)
T_s	is the system noise temperature (K)
SNR	is the required signal-to-noise ratio for detection
L_t	is the transmitter loss
L_α	is the atmospheric propagation loss
L_{bs}	is the beamshape loss
L_m	is the Intermediate Frequency (IF) amplifier bandwidth mismatch loss

Furuno 2125

The main radar parameters for the Furuno 2125 are listed in Table 9.2.1.

Transmit frequency	9410 MHz
Transmit power	25kW
Noise figure	6dB
Azimuth beam width	1.23°
Elevation beam width	20°
Rotation rate	24 r.p.m.
Antenna length	6ft

Table 9.2.1 Furuno 2125 parameters

From these parameters and by making educated guesses of the parameters not quoted by the manufacturer, the following, further parameters can be derived, see Table 9.2.2. Where convenient, values are quoted in decibels (dB).

Average power	5.3W short pulse 12.5W long pulse
Pulse repetition interval	0.33ms short pulse 1.0ms long pulse
Transmit gain and receive gain	32.2dB
Wavelength	0.032m
System noise temperature	1330K
Transmitter loss	2.0dB
Beamshape loss	1.8dB
Bandwidth mismatch	2.9dB short pulse 1.8dB long pulse
Range resolution	10.5m (min) short pulse 75m (min) long pulse

Table 9.2.2 Derived parameters for Furuno 2125

The radar cross section, σ, is set to 0.01m^2 corresponding to a large bird such as an 800g duck at X band.

The required signal-to noise ratio is calculated by assuming the following:

- All pulses during the time that the radar dwells on the target are integrated incoherently (26 pulse for short pulse and 8 pulses for long pulse)
- The probability of detection is set to 50%
- The probability of false alarm is set to 10-6
- The bird is a Swerling Case 1 target – a slowly fluctuating target during the radar dwell time

The atmospheric attenuation at 9410MHz is 0.024dB/km two way and the range estimate is carried out for (i) clear weather, (ii) 3mm/hr rain (light) and (iii) 10mm/hr rain (heavy, Barton 1988).

For each rain case, the calculation is carried out both for:

1. Ignoring the effect of backscatter from the rain.
2. Assuming that the target cannot be detected when the return from the rain backscatter is within 3dB of the return from the bird (signal-to-clutter ratio=3dB).

Weather	**Range / m (no clutter)**	**Range / m (clutter-limited)**
Clear	2187	n/a
3mm / hr	2166	950
10mm / hr	2108	305

Table 9.2.3 Detection range in short pulse mode (Pd=0.5, Pfa=10e-6, Swerling Case 1, 0.01 sq m target)

Weather	Range / m (no clutter)	Range / m (clutter-limited)
Clear	3197	n/a
3mm / hr	3154	355
10mm / hr	3035	110

Table 9.2.4 Detection range in long pulse mode (Pd=0.5, Pfa=10e-6, Swerling Case 1, 0.01 sq m target)

Tables 9.2.3 and 9.2.4 clearly indicate:

- The effect of attenuation due to rain at 9410MHz is negligible at these relatively short ranges
- The effect due to backscatter reflection from rain is dramatic, even at light rain precipitation levels (see discussion on constraints).

Furuno 2165

The Furuno 2165 represents the best detection performance available from an off-the-shelf marine navigation radar. The main radar parameters for the Furuno 2165 are listed in Table 9.2.5

Transmit frequency	3050 MHz
Transmit power	60kW
Noise figure	4dB
Azimuth beam width	2.3°
Elevation beam width	25°
Rotation rate	21 r.p.m.
Antenna length	9ft

Table 9.2.5 Furuno 2165 parameters

The derived parameters are given in Table 9.2.6

Average power	10.6W short pulse 43.2W long pulse
Pulse repetition interval	0.46ms short pulse 1.7ms long pulse
Transmit gain and receive gain	28.6dB
Wavelength	0.098m
System noise temperature	792K
Transmitter loss	2.0dB
Beamshape loss	1.8dB
Bandwidth mismatch	3.5dB short pulse 5.6dB long pulse
Range resolution	12.0m (min) short pulse 180m (min) long pulse

Table 9.2.6 Derived parameters for Furuno 2165

The radar cross section, σ, is set to 0.01m^2 corresponding to a large bird such as a 500g pigeon at S band.

The required signal-to noise ratio is calculated by assuming the following:

- All pulses during the time that the radar dwells on the target are integrated incoherently (40 pulse for short pulse and 11 pulses for long pulse)
- The probability of detection is set to 50%
- The probability of false alarm is set to 10-6
- The bird is a Swerling Case 1 target – a slowly fluctuating target during the radar dwell time

The atmospheric attenuation at 3050MHz is 0.015dB/km two way and the range estimate is carried out for (i) clear weather, (ii) 3mm/hr rain (light) and (iii) 10mm/hr rain (heavy)

Weather	Range / m (no clutter)	Range / m (clutter-limited)
Clear	3970	n/a
3mm / hr	3967	3450
10mm / hr	3958	1260

Table 9.2.7 Detection range in short pulse mode (Pd=0.5, Pfa=10e-6, Swerling Case 1, 0.01 sq m target)

Weather	Range / m (no clutter)	Range / m (clutter-limited)
Clear	5519	n/a
3mm / hr	5512	890
10mm / hr	5495	325

Table 9.2.8 Detection range in long pulse mode (Pd=0.5, Pfa=10e-6, Swerling Case 1, 0.01 sq m target)

Tables 9.2.7 and 9.2.8 indicate:

- The detection range is nearly twice that at 9410MHz
- The effect of attenuation due to rain at 3050MHz is negligible
- The effect due to backscatter reflection from rain is significant for heavy rain on the short pulse setting and for even light rain on the long pulse setting

Appendix 9.3 Radar detectability of birds

As pointed out by Bruderer et al. (1995), the implications of the radar equation in explaining the radar detectability of the targets (also birds) are usually not considered sufficiently by ornithologists. A simplified (i.e. excluding propagation losses) version of the radar equation is:

$$P_r = \frac{P_t \cdot G \cdot \sigma \cdot A}{(4\pi R^2)^2}$$

where P_r is the received power and R is the distance between the antenna and the target. The transmitted power P_t is concentrated to a certain sector due to the antenna gain G, and decreases in density on this way to the target by $4\pi R^2$. The energy reflected by the target depends on its size and reflecting properties, defined as its radar cross section σ. The reflected energy is again attenuated by $4\pi R^2$ on its way back. The received energy is proportional to the surface of the receiving antenna A.

The amount of RF energy reflected by a target is proportional to the radar cross section (RCS) of the target, usually expressed in m^2 or dBm^2. As a general rule, the RCS of a target increases with the physical size / cross section of the target. The RCS of a bird will fluctuate depending upon their aspect angle and the position of their wings. Typically, the RCS of a bird head-on is 8dB less than broadside. The reflection from wings contributes very little to the RCS but, because they can shield parts of the bird's body, it can cause significant variations to the RCS, typically 15 to 20dB. Suitably equipped radars to analyse the wing beat signature and thus, possibly, identify species can exploit this fluctuation.

The mean RCS of an individual bird is difficult to measure. However, Table 9.3.1 indicates measured and calculated mean RCS values for birds at S band and X band.

Table 9.3.1. Measured and calculated mean RCS values for birds and insects at S band and X band. It includes RCS of insects for comparison. Note -20dBm^2 corresponds to 0.01m^2 and -30dBm^2 corresponds to 0.001m^2.

Target	Mass (gram)	RCS at S band (dBm^2)	RCS at X band (dBm^2)
Duck	800	-30	-21
Gull	700	-30	
Pigeon	450	-21	-28
Lapwing	200	-22	
Grackle	130	-25	-28
Blackbird	100	-31	
Starling	75		-31
Sparrow	25	-28	-37
Chaffinch	24	-27	
Robin	17	-27	
Hawkmoth	1.2	-50	-39
Dragonfly		-64	-50

The measurements at S-band indicate the fluctuation of RCS in the Mie[1] region, whereas, the measurements at X-band indicate a steady decrease in RCS with decreasing mass. It is anticipated that the RCS of birds at frequencies above X-band will follow those at X band. Note that the RCS of a group of birds is the incoherent summation of the individual RCS, i.e. the amplitude sum of the RCS'. This can be used to provide an approximation of flock size, if species is known. The RCS values of individual insects are significantly less than those of birds. However, the cumulative RCS of a 'swarm' of insects can be similar to that of a bird(s) and can lead to false target detection.

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[1] The Mie region, also called the resonance region, corresponds to the range of target sizes where the radar return consists of specular reflection from the front of the target (sphere) constructively and destructively interfering with a creeping wave going around the target (sphere). It is generally accepted that this occurs between ka=1 and ka=10, where ka=2⦸*a/☒ (a is the radius of a sphere). Ka is therefore a measure of the circumference of the target expressed in wavelengths.

Appendix 9.4 Effects of atmospheric conditions on radar detectability of birds

The detection performance of radar is affected by atmospheric attenuation. At RF frequencies corresponding to absorption by gas molecules such as oxygen and water the RF signal can be heavily attenuated and the radar detection range is reduced. Therefore, radar detection performance is significantly affected by rain and snow precipitation and by fog. In the microwave region the reduction in performance worsens with increasing frequency. Conventional marine navigation radars often have a facility for reducing the effect on the radar PPI display of rain clutter. Whilst this apparently clears the radar picture of rain clutter it reduces the radar's sensitivity against birds.

When studying birds that migrate at low altitude over the sea, sea clutter at the PPI can reduce and sometimes totally remove all bird echoes. As was for rain clutter, sea clutter can be removed by the anti-rain-clutter facility which will eventually also reduce the radar's sensitivity against birds.

Appendix 9.5 Correcting for changes in detection probability of a bird with increasing distance from a radar antenna

Whether or not a bird is detected by radar depends on quite a number of factors (Eastwood 1967, Bruderer 1997a, b). The volume covered by a radar beam increases with distance. On the other hand, the energy density of emitted radar beams decreases by the factor $4\pi R^2$ (where R = distance), and the same energy loss occurs with the radar beams reflected by birds. This results in a complex relationship between the distance to an object and the probability of the object being detected by radar. In order to compensate for this distance-related ”sensitivity” of radar equipment when undertaking quantitative assessments (e.g. regarding the altitude or other distributions), the number of echos recorded has to be corrected for this change in detectability with distance from the radar antenna.

Hüppop et al. (2002) provides a useful worked example of this type of approach using a distance correction for detectability. They used a half-normal model with cosine series expansion (Buckland et al. 2001) was used, with three parameters to be estimated (a1-3)), which constitute a good compromise between a good fit (assessed according to the Akaike Information Criterion) and easy handling of the model. They showed that the method is entirety satisfactory for the determination of relative flight intensity up to distances of just under 2,000 m using their equipment. At larger distances, the density of values per 100 m x 100 m field is underestimated. A distance correction has to be performed for each individual radar unit because of production-related differences and different equipment settings. Of course, it is important to emphasise that settings must not be changed after such a “calibration”, unless its effect on the radar performance have been studied through careful testing.

Appendix 9.6 A brief description of how Schweizerische Vogelwarte Sempach carry out calibration measurements on their "Superfledemus" radar.

Measuring the transmitter power output

The power output of the magnetrons decreases with time. In addition, the high power setting does also have an influence on the peak power output. Therefore, we measure before and after each field season the power output with the Radar Test Set HP 624C, by directly connecting the test set to the antenna. Based on a temperature sensitive resistance, mean power is measured. As pulse repetition frequency is known (in our case 2083 kHz) and impulse width is also measured, we get the peak power output. According to our experience our power output is normally stable. However, the measurement allows a general control of the transmitter.

Measuring the noise level

According to thermal effects (or whatever) noise can vary between measurements. Before each density measurement (conical scanning or fixed beam measurements) the beam is set towards a direction with no ground clutter. The video sampling unit undertakes several measurements (ca. 20s) to achieve an automatic threshold for the noise level (based on the frequency distribution of noise peaks). This information is stored with each density measurement. This threshold is used in the subsequent analysis.
After we have changed our receiver to a new log receiver the noise level is more or less stable. We do have more instability within the tailor made video sampling unit.

Measurement of the receiver sensitivity

This is the most important measurement. It allows us to assign the synthetic values coming from the receiver signal and digitised in the video sampling unit to real dBm-values. With the aid of the radar test set or a X-band generator, a calibrated signal is directly fed into the radar system. The calibrated signal is reduced step by step throughout the total dynamic range of the receiver (in our system about 60dB). The result is a calibration curve permitting assignment of a dBm-value to all measured synthetic values. This measurement is done for each individual radar at the beginning and at the end of each field season (ca. 3months). This measurement is delicate and needs an accurate measuring system and an experienced technician. This measurement allows a general examination of all parts involved in receiving the echo signal (wave guide, mixer, preamplifier, log-amplifier, dynamic range and sensitivity).

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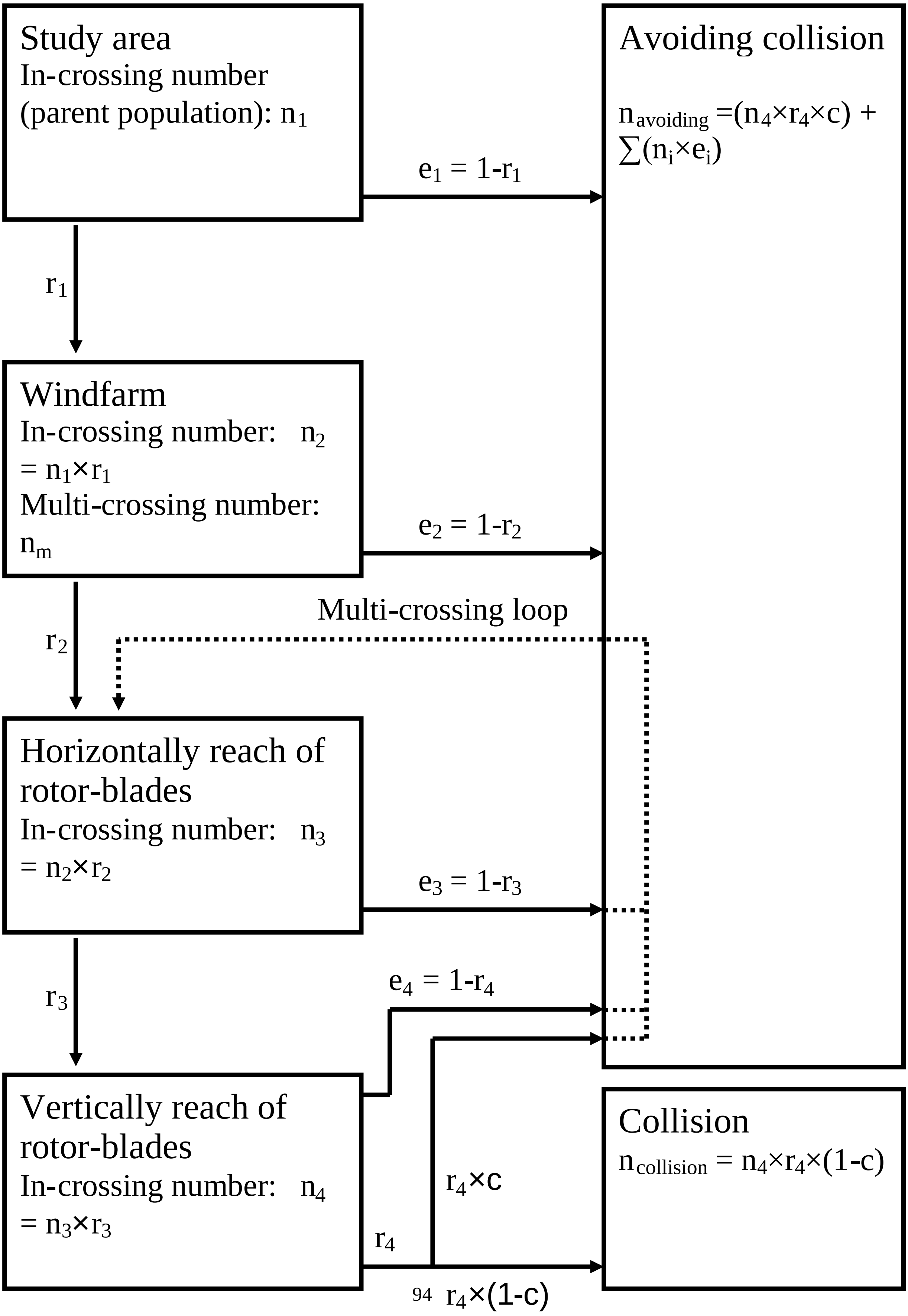
28th April 2005

Figure 4.3.1


Study area
In-crossing number (parent population): n_1
$e_1 = 1-r_1$
r_1
Avoiding collision
$n_{avoiding} = (n_4 \times r_4 \times c) + \sum(n_i \times e_i)$
Windfarm
In-crossing number: $n_2 = n_1 \times r_1$
Multi-crossing number: n_m
$e_2 = 1-r_2$
r_2
Multi-crossing loop
Horizontally reach of rotor-blades
In-crossing number: $n_3 = n_2 \times r_2$
$e_3 = 1-r_3$
r_3
$e_4 = 1-r_4$
Vertically reach of rotor-blades
In-crossing number: $n_4 = n_3 \times r_3$
r_4
$r_4 \times c$
Collision
$n_{collision} = n_4 \times r_4 \times (1-c)$
$r_4 \times (1-c)$