Title: Challenges and Solutions of Remote Sensing at Offshore Wind Energy Developments

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Abstract: Radar is becoming an important tool used to gather data on bird and bat activity at proposed and existing land-based wind energy sites. Radar will likely play an even more important role at the increasing development of wind energy offshore, given both the lack of knowledge about bird and bat activity offshore and the increased difficultly in obtaining offshore information. Most radar studies to date have used off-the-shelf or modified marine radars. However, there are several issues that continue to hinder the potential usefulness of radar at wind energy sites, with offshore sites providing a particular suite of challenges. We identify these challenges along with current or developing solutions.

Keywords: radar; offshore; wind energy; remote sensing; wave clutter

1. Introduction

Radio detection and ranging (radar) has been used to detect birds as early as 1940 (Eastwood 1967) and has increasingly been used to investigate activity of birds, bats, and insects since then (Bruderer 1997, Gauthreaux and Belser 2003, Larkin 2005, Lilliendahl et al. 2003, Vaughn 1985). However, radar has only recently been applied to detect aerial biological targets at wind energy sites (Desholm et al. 2006, Harmata et al. 1999 & 2000, Mabee and Cooper 2004, Mabee et al. 2006) but is already included as a survey option in several guidance documents for wind energy development (e.g. EC-CWS 2007a, b, NYSDEC 2009, Rodrigues et al. 2008, USFWS 2003). Radar technology can be applied to pre-construction surveys (detecting activity present for collision risk assessments), post-construction monitoring (validating pre-construction assessments or detecting changes in activity), and also mitigation (radar-triggered mitigation during high-risk time periods).

Most radar studies at wind energy sites have been at land-based locations, however wind energy has recently began to develop offshore. Radar will likely play an even more important role at the increasing development of wind energy offshore, given both the lack of knowledge about bird and bat activity offshore and the increased difficultly in obtaining this information. Although a few radar studies have already been attempted offshore (e.g. Denmark, Scotland, the Netherlands, Germany, and most recently, the nearshore in the USA), using radars offshore provides several unique challenges beyond the traditional difficulties recognized at land-based sites. We present these challenges along with solutions or new technology developed to deal with these issues. Three offshore specific challenges include wave clutter, detecting and tracking birds directly on or above the waters surface, and interference from radars used for boat navigation. These challenges are in addition to four other issues that have already been recognized at land-based sites but nevertheless must still be dealt with offshore, often under more extreme conditions: precipitation, turbine shadow, distinguishing target type, and mitigation.

2. Remote sensing challenges specific to offshore

2.1 Wave clutter

Problem: Waves on the waters surface present a special challenge for radars. The surface of a wave oriented towards a radar strongly reflects radar energy creating non-target returns, or wave clutter. Wave clutter can prevent the detection of a biological target in the same area if its return is weaker, and the more that wave clutter fills a radar sampled area the less area biological targets can be detected within. Ultimately, differences between detectable areas complicate comparisons over time or between locations. As waves are so dynamic, a different distribution of wave returns is produced during each scan of a radar. This makes it difficult to create clutter maps that are commonly used to eliminate ground clutter for land-based radars. The constant "movement" of the returns created by wave clutter can also produce false tracks if tracking algorithms cannot adequately separate wave clutter from true biological targets.

Solutions: The easiest solution is to use a *vertically scanning* marine radar instead of a horizontally scanning marine radar. Although marine radars usually scan horizontally, they can also scan vertically as described by Harmata et al. 1999. Vertically scanning radars minimize the area of water surface that is detected, and also provide altitude data (important for assessing biological target movements within rotor swept zones of wind turbines) and better data for counting biological targets moving through the area.

Another type of radar that can also sample vertically are *vertical profiling radars*. These radars are fixed beam radars pointed vertically, similar to a flashlight, and record the altitude and reflectivity of targets as they pass through the field of view. They sample above the water's surface, and so avoid the wave clutter issue altogether. However, the restricted horizontal coverage of vertically sampling radars severely limits the collection of target directional data, and provides only limited information on biological targets directly on or above the water's surface in the narrow field of view of the radar (typically about five degrees). Therefore, if these types of data are necessary to answer specific research questions, horizontally scanning radar are necessary.

If horizontal radar data such as direction is desired over water, one solution is to use a *radar fence* with a horizontally scanning antenna to create an artificial radar horizon. Radar fences usually are metal fences, sand dunes or other terrestrial topography that absorb radar energy in the lower portion beam, preventing the detection of ground clutter that would normally obscure targets detected in the upper portions of the radar beam. For offshore applications, a radar fence can also be a tube or flat metal plate positioned in front of the lower portion of the antenna, extending the length of the antenna, and sometimes including a layer of radar absorbent material. This creates an artificial radar horizon above the surface of the water, eliminating the detection of waves and allowing the detection of biological targets above the water's surface. However, in order to eliminate wave detection the radar fence would likely be positioned to prevent detection of all but the highest waves, which would also eliminate the detection of any biological targets directly on or above the water's surface.

In order to move one step closer to detecting targets' direction on or above the waters surface while still eliminating wave clutter *static clutter maps* based on worst-case sea states can be used. Typical land-based clutter maps allow the removal of ground clutter and the retention of biological targets by using previous scans to quantify the signal strength of returns from static targets producing ground clutter. Therefore, targets are detected when energy returns greater than the background signal are detected. However, wave clutter is dynamic and does not allow for static returns to be captured. One solution would be to use background signal strength from wave returns during the worst-case wave conditions, and then plotting and storing these returns in a static clutter map. The disadvantages of this technique include the requirement for data collection prior to a survey, waiting for worst-case wave conditions to occur, and degraded target detection during all sea conditions. However, the probability of detection would be constant over all conditions making radar data recorded during different sea states still comparable. Consistent, comparable radar data provides more accurate trend data, and is preferable over data that may provide a greater detection probability during low sea-state but an inconsistent probability of detection during other sea conditions.

2.2 Detecting and tracking birds directly on or above the waters surface

Problem: Many waterbirds such as ducks, geese, gulls and terns will fly or soar very close to the waters surface. These birds will also rest directly on the water's surface. Changes in waterbird behavior or movement patterns (e.g. seasonal migration, daily commuting), and loss of roosting or foraging habitat are both possible impacts to birds from offshore wind energy development. In order to fully document these types of impacts, detection of birds directly on or above the waters surface is necessary. To include detection of these biological targets, more complex radar solutions are needed.

Solutions: *Scan-to-scan integration correlation* is a technique used to detect stationary or slow moving targets on the water's surface (e.g. pieces of floating ice) and requires faster than normal antenna rotation; this technique does not work for fast moving targets (Ryan 2008). A typical marine radar antenna scans about 18-28 rpm, compared to the high speed rotation of 40-120 rpm needed for this technique. Basically, this technique uses a large number of previous radar images (ranging from 2 to as high as 128) and integrates them to create one composite image. This ultimately smoothes away both the wave clutter and impulse noise from the radar receiver, and makes stationary objects visible as point targets (Figure 1) and slow moving targets visible as "slug tracks". The process involves first collecting raw radar data digitally from a fast-rotating radar and recording it to data files along with GPS and target heading data. Then a large numbers of scans from the same azimuth and range are integrated into a single image with compensation for ship motion. This effectively minimizes clutter from waves and receiver impulse noise while enhancing the signal strength of small, stationary or slow moving targets. Validation of targets, such as rafts of waterfowl on the water's surface during nights, can be done with thermal imagery or night vision equipment. Both the radar data files and ground truth observations can be transferred to GIS for further analysis.

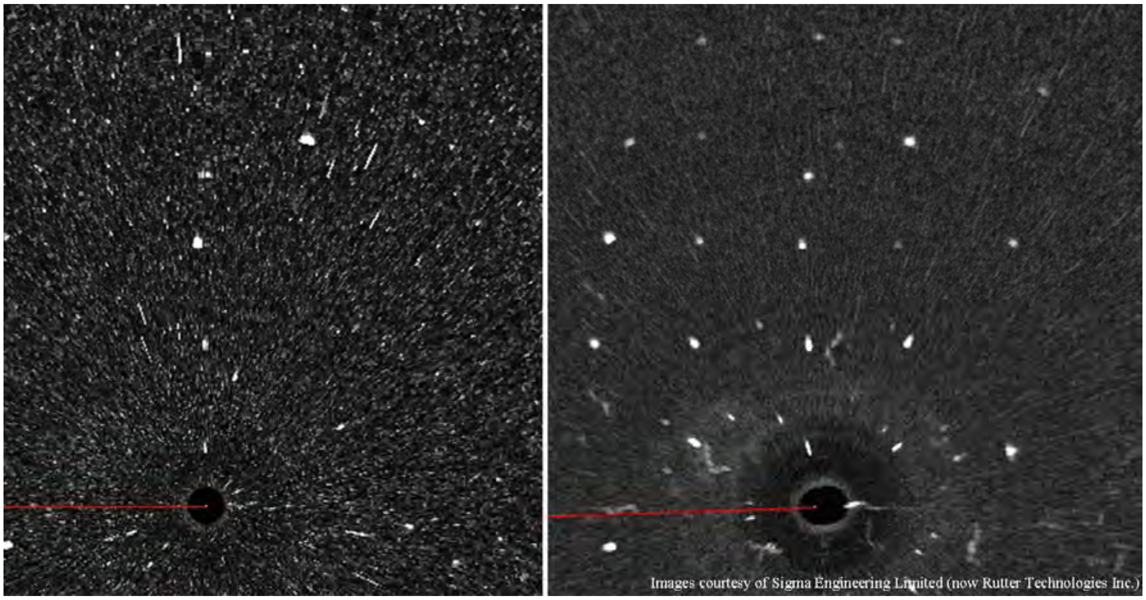
Images courtesy of Sigma Engineering Limited (now Rutter Technologies Inc.)

Figure 1. Radar images over water demonstrating wave clutter (left) and application of scan-to-scan integration correlation (48 scans) to the same image (right).

Frequency Diversity Processing is a technique, used by non-Doppler radars with magnetrons in addition to coherent and solid state radars, that alternates the transmission of two frequencies from pulse to pulse. This allows the wave phase to change as it moves down the wave guide and as the radar beam transmits in two slightly different directions during each alternating pulse, any point is scanned approximately 20-40 ms apart by the two pulses. Signal processing then integrates the signal strength of the two pulses. Wave clutter will have rapid radar cross section variation making radar returns inconsistent, therefore averaging a lower signal return value as opposed to target echoes which will have more consistent returns. Moving biological targets (e.g. birds with flapping wings) will also have variable radar cross sections but the small temporal interval (20-40 ms) between the pulses will only allow for a small change compared to that from waves. The disadvantage of this technique is a requirement for two transmitters along with synchronized receivers, adding significant cost to the radar equipment.

Doppler processing can be used to accurately differentiate between the velocities of slow moving waves and faster moving bird or boat targets. This technique requires the use of Doppler, or coherent radars, which start and stop transmission at a known phase in the waveform allowing accurate Doppler shift measurements. The velocity differences can be used along with tracking algorithms to separate small, weak bird targets from a background of stronger wave targets.

2.3 Interference from other radars

Problem: Radars active in close proximity to one another can cause interference in the radar data, often portrayed as radial lines. On a radar display, these radial lines look like spokes on a bicycle wheel. This can be a common problem when using radars offshore, as most ships use marine radars for navigation. X-band radars are more frequently used by ships than S-band, as they are generally cheaper. Therefore, S-band radars will likely experience less interference than X-band radars.

Solution: Radial lines caused by interference from other radars can be reduced to a small point using CFAR processing (Figure 2). CFAR (Constant False Alarm Rate) is a standard and established processing technique in the radar community that basically reduces the radar data to the highest intensity peaks. The points remaining from the radial lines could potentially be mistaken for biological targets. Therefore, interference rejection algorithms in combination with care in correlating plots to target tracks can minimize this problem. We have tested two different types of interference rejection algorithms. The first has proven to be 90-95% successful in preventing these residual points from being falsely correlated with target tracks. The second has the potential to be up to 100% effective, but has not yet been integrated into the software, and needs to be tested on both magnetron and solid state radars.

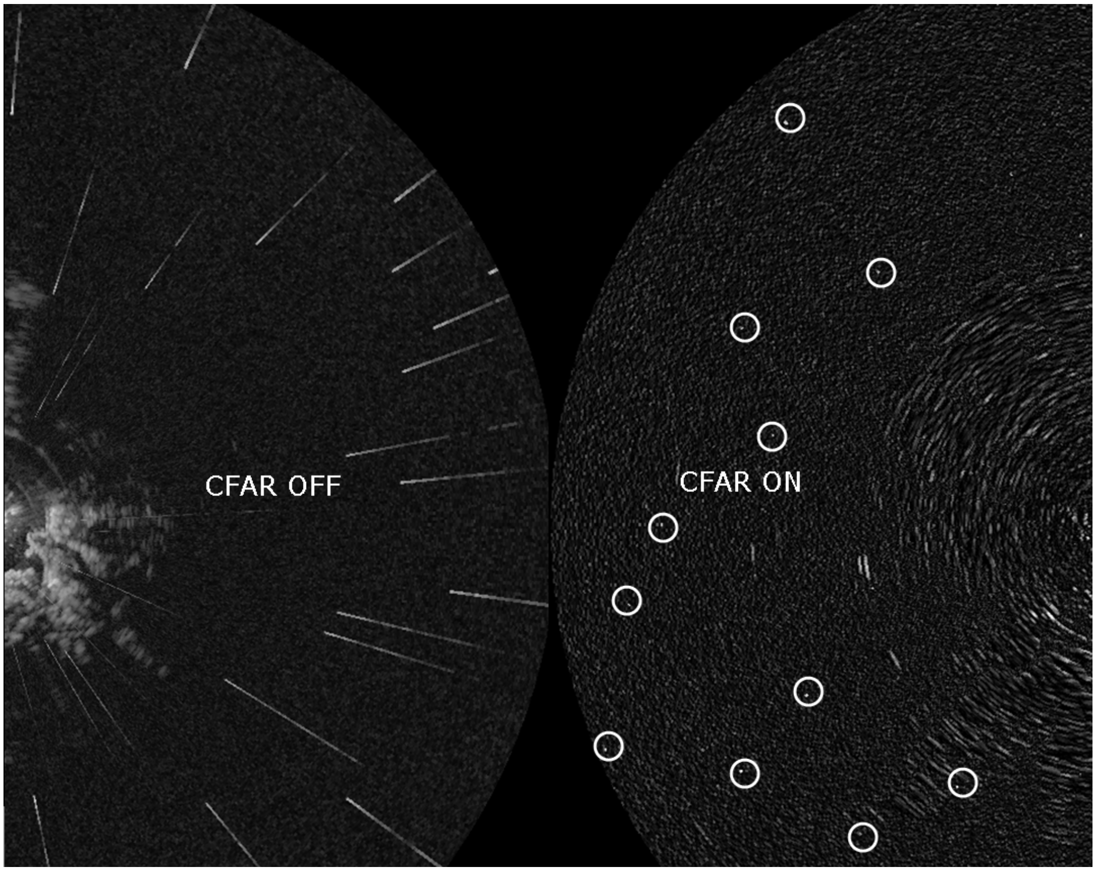

Figure 2. Interference from other nearby radars can cause interference in the radar data, resulting in radial lines (left), which can be reduced to points (noted with white circles) using the CFAR algorithm (right).

3. Remote sensing challenges at all wind energy sites

3.1 Precipitation

Problem: Precipitation saturates X-band radars (3-cm wavelength), regardless of how they are positioned, leaving the radar unable to detect biological targets during precipitation events (e.g. rain, snow, and heavy fog). We know targets move in the rain, and in fact, the collision risk of birds is associated with inclement weather during migration (Manville 2005). For offshore wind energy application, this association makes it especially important to be able to document and detect biological target movements during precipitation events.

Solution: Although the 3-cm wavelength of X-band radars becomes saturated by precipitation, the larger, 10-cm wavelength of S-band radars is still able to detect biological targets in precipitation with proper digital processing (Figure 3). First, precipitation is removed using the CFAR algorithm, which reduces the radar data to the highest intensity peaks within a given scan. This effectively removes the precipitation, leaving behind targets and clutter. A tracking algorithm can then be used to separate the remaining stationary ground clutter from the moving targets. It does this by comparing the current scan to previous scans and if a target has moved (and satisfies the other criteria of a biological target as built into the tracking algorithm) it is retained. As clutter generally does not move, it is easily removed. Specialized tracking algorithms are needed to separate wave clutter from moving targets.

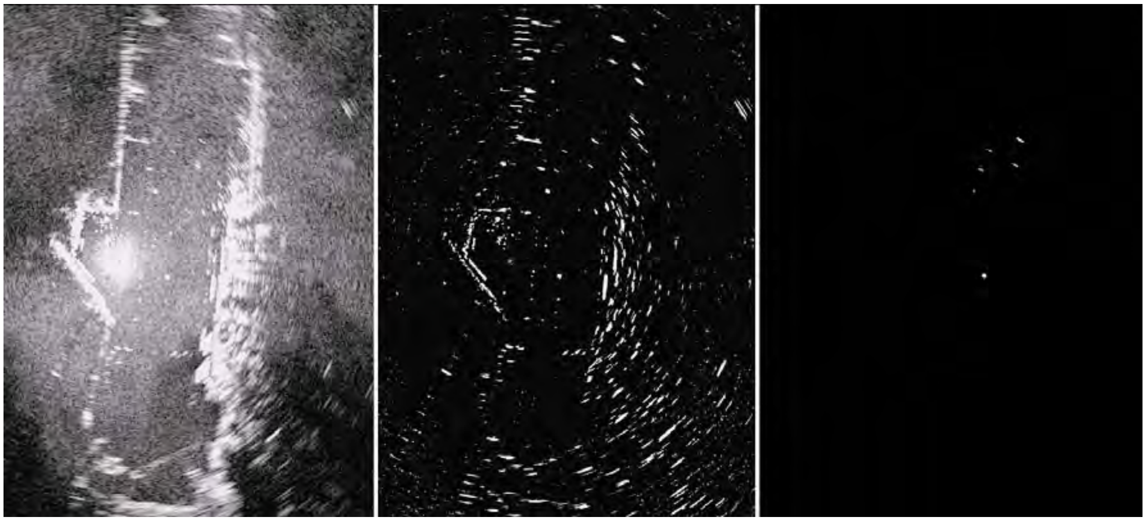

Figure 3. Radar images from a horizontal-scanning S-band radar showing precipitation (left), application of CFAR algorithm that removed rain and left behind targets and some clutter (middle), and application of a tracking algorithm leaving only moving targets (right).

It is possible to remove rain from the data of X-band radars that are fixed beam radars, but currently the removal of rain from scanning X-band radars is technically extremely difficult and requires equipment four to five times more expensive than simply obtaining an S-band radar.

3.2 Turbine shadow

Problem: A turbine shadow is defined as the area blocked by a wind turbine and is where radar is unable to detect targets. A target may be lost either when passing behind the turbine (as radar energy blocked is by the turbine structure) or in front of the turbine (the large amount of radar energy reflected by the turbine structure does not allow a target with less reflectivity to be detected in front of it). Whether a target is lost in a turbine shadow depends on both the size of obstruction and the tracking algorithm specifics. Two limitations produced by turbine shadows are less certainty that the emerging target is the same as the entering target (leading to undercounting), and the possibility that the target may be counted twice if a specific tracking algorithm allows the track to be broken (leading to inflated target counts).

Solution: Newer Doppler radars can theoretically detect small difference in reflectivity of a bird in front of a turbine shadow with stationary blades, but moving turbine blades create a Doppler shift that cannot currently be ignored. Therefore, one currently available solution is to mark range bins occupied by turbine blades and eliminate anything detected in these areas. This eliminates false targets induced by turbine blades, and provides a consistent area of detectability. Disadvantages include a reduced area in which targets can be detected within, and a greater probability that tracks around marked turbine shadows will be broken, potentially leading to overcounting.

Tracking algorithms are another solution that would still allow targets to be detected within or behind turbine towers or blades. The advantage of tracking algorithms over human observers is that they are applied consistently, always use the same rules under all conditions, and when biases exist they are created consistently. Disadvantages include the inability or difficulty in preventing the tracking of moving turbine blades, and difficulty in determining the appropriate amount of time that can be allowed to pass without a track before a track is broken. Allowing too little time will not permit biological targets to move behind a turbine without the track breaking, but allowing too much time without a track detected may permit unrelated tracks to be joined.

3.3 Target categorization

Problem: Currently, data from marine radar cannot categorize biological targets into birds, bats, insects, individual species, or species groups without validation such as bat detectors or thermal imagery. Categorization into these types of groups is desired as it allows more detailed information on movements of birds, bats and insects, and also allows for discovery of interactions between those specific groups, or between each of these groups and weather conditions or wind turbines. This in turn could elucidate factors driving bird and bat movements near wind turbines, identify high-risk time periods, and aid in developing mitigation strategies.

Solution: Tracking radars have been used to track individual, flying biological targets, distinguish between bird and bat, and identify a target to a specific species using recorded wing-beat patterns (Bruderer and Popa-Lisseanu 2005, Zaugg et al. 2008). These types of target categorizations are based on the modulation rate of the radar echo produced by the target's wing-beat as it is tracked by the radar beam for up to several seconds (Eastwood 1967). The fluctuations in reflected energy are related to rapid changes in the circumference and volume of the target's body (Bruderer 1997) due to the movements of wings and associated flight muscles during powered flight. The fundamental frequency of the resulting rhythmic pattern is generally related to the wing-beat frequency of the target.

Wing-beat frequencies are measured as the number of flapping cycles per second for a phase of continuous flapping. From the smallest insects to the largest birds, wing-beat frequency is proportional to the body mass of the animal, with the smallest targets (insects) generally have the fastest wing-beat frequencies and the largest targets (birds) the slowest. Many small birds intersperse periods of continuous flapping with periods of gliding, allowing wing-beat patterns as well as frequency to aid in target identification. When combined with sufficiently ground-truthed algorithms, these data may be used operationally to discriminate between birds, bats and insects, or even identify certain species.

Tracking radars, however, have not been widely used due to their high cost, maintenance, and operational complexity. Therefore, we have developed a vertical profiling radar (VESPER™ Vertical Profiler Radar) with a narrow (2-4°) fixed beam that has the same capability of measuring wing-beat frequencies as tracking radars (Figure 4), but uses more reliable and lower cost components. The 2-4° beam width is sufficiently wide to allow even large, slow flapping targets to reside in the beam for several seconds allowing for wing beat measurement. These vertical profiling radars are able to produce very detailed density, altitude, and target type information, but are not limited to a single target, instead recording all aerial targets within the beam. In addition to producing data that allows for better target categorization, the vertical profiler radar has no moving parts, does not detect wave clutter (as it only detects above the water's surface), is not saturated by precipitation (when a large number of pulses are integrated) and can be used independently or to validate other radar data, including NEXRAD.

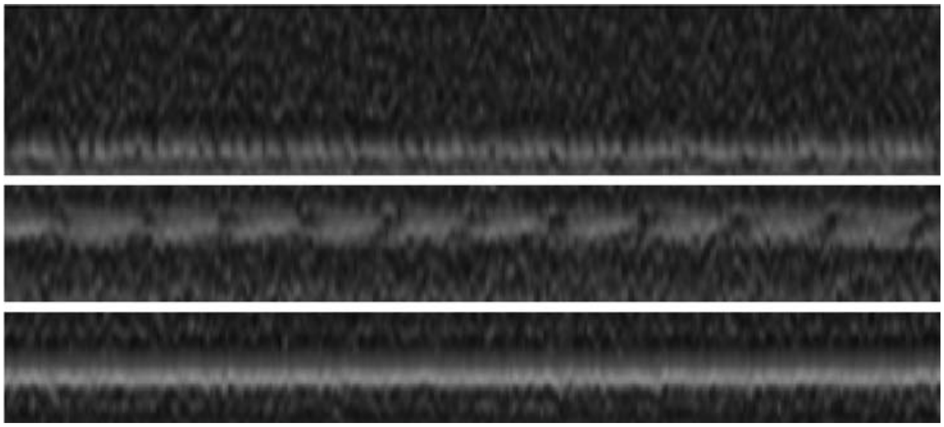

Figure 4. Rhythmic patterns of reflectivity resulting from the wing-beat pattern of a small target (top) and larger target (middle); aircraft result in a sold line (bottom). Horizontal axis is time; vertical axis is distance from radar.

3.4 Radar-triggered mitigation

Problem: Although generally perceived to have low environmental impacts, a number of wildlife impacts at wind energy facilities have been documented. In particular, collision fatalities of birds and bats have been found at wind turbines world-wide (e.g. Atienza et al. 2008, Bevanger et al. 2008, Erickson et al. 2001, Erickson et al. 2002, Hall and Richards 1972, Johnson 2005, Orloff and Flannery 1992, Rodrigues et al. 2008,). The potential for undiscovered risks and cumulative effects of known mortality continue to be a very real concern as wind turbines are being placed in new regions with different habitats, weather conditions, and topography. Potential impacts at offshore wind energy facilities are particularly concerning given that information on bird and bat movements and behavior are both less known and more difficult to obtain offshore compared to terrestrial locations. In order for wind energy to continue developing into a sustainable renewable energy source, it has become necessary to have mitigation options that will address these issues while minimizing lost generation time.

Solution: In order to minimize collision risk of birds and bats at wind turbines, it has been proposed to shut down turbines, or feather the turbine blades minimizing rotation, during time periods of high collision risk. These high risk periods are usually based upon associations made with high mortality time periods that were either measured or modeled. As wind turbine downtime equates to lost revenue, the narrowest risk time periods possible are preferred. However, a lack of detailed understanding of when and why bird and bat mortality occurs, particularly offshore, often make these high-risk time periods quite large and potentially economically unfeasible. Therefore, real-time identification of high-risk time conditions is desired to minimize both bird and bat collision risk and turbine downtime.

With an objective of mitigating strike risk of birds and bats at operational wind farms, we have developed a MERLIN™ *SCADA* system that integrates avian radar technology with the wind farm operating system. This radar system functions as a continuous monitoring and control system at operational wind farms and is capable of activating mitigation measures during conditions associated with high bird or bat mortality risk. Potential mitigation measures generally involve idling turbines via the wind farm's operating system, or Supervisory Control and Data Acquisition (SCADA), when pre-set conditions indicative of high strike risk have been met.

The MERLIN™ Avian Radar System uses advanced avian radar technology to detect and track birds and bats in real-time using simultaneous vertical and horizontal scanning radars. This radar system is also used to conduct the pre-construction surveys necessary to identify high strike risk conditions at a proposed wind energy site. The MERLIN™ *SCADA* system can then be programmed with a rule set based on these high strike risk conditions. When this rule set is satisfied during operation of the MERLIN™ *SCADA* system, MERLIN™ software uses the industry standard Modbus communication protocol to communicate with the wind farm's operating system to initiate a variety of response actions, ranging from alerting wind farm operators to direct instruction of a turbine or groups of turbines. The MERLIN™ system then continues to monitor the bird and bat activity, providing an “all clear” response (e.g. restarting the idled turbines) once the risk level lowers. This effectively reduces the amount of wind turbine downtime to only periods of time when high collision risk is actively detected.

The application of the MERLIN™ *SCADA* mitigation requires the development of site-specific rule sets as each site has different topography, geographic region, species composition, species movement patterns, climate, etc. It is important for site-specific pre-construction studies to adequately describe circumstances under which strikes are likely to occur so rule sets can be refined to optimize mitigation. This mitigation technique would allow reduction of turbine downtime by targeting exact periods of high mortality risk, and may provide an important tool in a comprehensive mitigation process for wind energy companies to reduce bird and bat strike risk at wind farms.

Disclosure statement

All authors are employees of DeTect, Inc (DeTect). After recognizing the challenges of offshore remote sensing, DeTect has and continues to develop radars and radar systems in an attempt to overcome these challenges. DeTect also markets this technology, specifically the MERLIN™ *SCADA* system, the MERLIN™ Avian Radar System, the VEPSER™ vertical profiler, and the MERLIN™ interference rejection algorithms.

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