THE UNIVERSITY OF TEXAS AT AUSTIN

Final Report DE-EE0005380
Assessment of Offshore Wind Farm Effects on Sea Surface, Subsurface and Airborne Electronic Systems

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U.S. Department of Energy

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9/30/2013

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Acknowledgments

For their support of this report, the authors thank the entire U.S. Department of Energy (DOE) Wind & Water Power Technologies Program team, and in particular Brian Connor, Gary Norton, Bryan Miller, Michael Hahn, Gretchen Andrus, and Patrick Gilman. For providing key input and reviewing elements of this report, we also acknowledge:

George Detweiler, USCG; Daniel Freedman, USCG; Tim Crum, NOAA; Ed Ciardi, NOAA; Jack Harlan, NOAA; Pete Lessing, NOAA; Nick Shay, University of Miami; Edward Davison, NTIA; Tracy Cassidy, DHS; John Yarman, Air Force; Dave Belote, DOD; Frederick Engle, DOD; John Zentner, NORAD; Lynne Neuman, AFSPC; Walter Schobel, AFSPC; Dwight Deakin, NAVAIR; John Page, FAA; Douglas Klauck, FAA; Don Bui, FAA; Jeff Bogen, FAA; Rajiv Gautam, FAA; Stephen O'Malley, Fishermen's Energy; Clark Speicher, Lockheed Martin; Kurt Olsen, Lockheed Martin; Charles Liang, Lockheed Martin; Klaus-Werner Gurgel, University of Hamburg; Lucy Wyatt, James Cook University; Donald Barrick, CODAR Ocean Sensor; Calvin Teague, CODAR Ocean Sensor; Kathleen O'Neil, NOAA;Peter Hughes, Fishermen's Energy; Fred Pease, DOI; Brian Kent, Air Force; John Stubstad, DOD; Nick Ferratella, Navy; Wesley Bomyea, Navy; George Ioup, University of New Orleans; Juliette Ioup, University of New Orleans; Grayson Rayborn, University of Southern Mississippi; Shawn Rice, ION GeoVentures; Dale Lambert, ION GeoVentures; Craig Beasley, Schlumberger; Clifford Frohlich, University of Texas at Austin; Raymond Soukup, ONR; George Thomas, USCG; Rodney Nelson, Schlumberger; Melissa Sanderson, Cape Cod Commercial Hook Fisherman's Association; Joseph Rice, Naval Postgraduate School; Kenneth Krueger, ARL:UT; Christopher Tiemann, ARL:UT; Nicholas Chotiros, ARL:UT; Rick Bailey, ARL:UT; Gary Wilson, ARL:UT; Megan Ballard, ARL:UT; Frank Stone, Navy; James Miller, University of Rhode Island; Gopu Potty, University of Rhode Island; Megan McCluer, Air Force; Jose Zayas, DOE; Joel Cline, DOE; Russell Wright, DHS; Joel Wall, DHS; Donald Fraser, DHS; James Baird, FAA; E. J. Beaulieu, FAA; Mark Carmouche, FAA; Mike Hensley, FAA; Michael Aimone, DOD; William Van Houten, DOD; Louis Husser, DOD; Paul Karch, DOD; Kimberly Stroud, DOD; Mark Bishop, NORRAD; Shawn Jordan, Air Force; Franz Busse, MIT Lincoln Lab; Richard Younger, MIT Lincoln Lab; Christopher Keck, MIT Lincoln Lab; Jason Biddle, MIT Lincoln Lab; Howard Swancy; David Minster, Sandia National Labs; Milford Estill, Sandia National Labs; Benjamin Karlson, Sandia National Labs; Bruce LeBlanc, Sandia National Labs; Leroy Garley, Sandia National Labs; Lenore Boulton, Sandia National Labs.

Table of Contents

Executive Summary

Background: Offshore wind energy is a valuable resource that can provide a significant boost to the US renewable energy portfolio. A current constraint to the development of offshore wind farms is the potential for interference to be caused by large wind farms on existing electronic and acoustical equipment for surveillance, navigation and communications. Therefore, the U.S. Department of Energy funded this study as an objective assessment of possible interference to various types of equipment operating in the marine environment where offshore wind farms could be installed.

The interference due to land-based wind farms on radar under certain circumstances has already been widely publicized and studied. The rotation of the turbine blades can give rise to strong Doppler clutter, which can interfere with the operation of existing military, aviation and weather radar systems. In Europe, investigations on the effect of offshore wind farms on marine navigation have been conducted as early as 2004. To date, no comprehensive study of the potential for electromagnetic interference has yet taken place in the US for offshore wind farms. This is due in large part to the lack of any operating offshore wind farms in the US.

For acoustics, while there have been many studies of whether airborne noise generated by wind turbines impacts communities, none was found describing how the sound radiated underwater by offshore installations impacts acoustical equipment. Except in relatively close proximity to the wind farms, a distance that depends on many factors including environmental and those specific to the wind farm itself, the radiated sound pressure levels are comparable to ambient noise levels in coastal waters.

Objective: The objective of this project was to conduct a baseline evaluation of electromagnetic and acoustical challenges to sea surface, subsurface and airborne electronic systems presented by offshore wind farms. To accomplish that goal, the following tasks were carried out:

i. Survey electronic systems that can potentially be impacted by large offshore wind farms, and identify impact assessment studies and research and development activities both within and outside the US,
ii. Engage key stakeholders to identify their possible concerns and operating requirements,
iii. Conduct first-principle simulations on the interactions of electromagnetic signals with, and the radiation of underwater acoustic signals from, offshore wind farms to evaluate the effect of such interactions on electronic systems, and
iv. Provide impact assessments, recommend mitigation methods, prioritize future research directions, and disseminate project findings.

This report was produced on behalf of the Wind and Water Power Technologies Program within Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE), under grant number DE-EE0005380. The award resulted from Funding Opportunity Announcement DE-FOA-0000414, entitled U.S. Offshore Wind: Removing Market Barriers, Topic Area 7: Impact on Electronic Equipment in the Marine Environment.

Methodology: A survey of electronic equipment (marine radar, airborne radar, sonar, navigation and communications equipment) that could potentially be impacted by large offshore wind farms was first carried out. The electromagnetics and acoustics teams each developed a systems list (systems listed vs. frequency and applications/stakeholders). In addition, a review of both US and non-US literature related to wind farm interference on electromagnetic and acoustic systems was conducted. For electromagnetic systems, the literature was grouped into marine navigation, air traffic control, weather and ocean monitoring, air defense and long-range surveillance, communications systems, and mitigation techniques. For underwater acoustic systems, the literature was grouped into noise measurements, impact on marine mammals, impact on fish/fisheries, and mitigation techniques.

Next, the project team engaged several key stakeholders in government and industry to identify concerns on interference from offshore wind farms, characterize potential impact to operations, determine known requirements and options for mitigation, and establish research needs. In-depth personal interview was chosen as the appropriate research approach to gather technical information and opinions on the subject matter from a wide range of stakeholders in both electromagnetics and underwater acoustics. Interviews were carried out to understand past experiences with land-based wind farm interference and potential concerns with future offshore wind farms on various systems operated by the stakeholders. Through this process, key technical issues were identified and addressed in the subsequent modeling study.

The electromagnetic modeling effort focused on the most important cases identified through literature survey and stakeholder interviews. These cases include marine radar, airborne radar, HF radar, and communications systems. Electromagnetic modeling of utility-scale, horizontal-axis wind turbines was carried out using high-frequency ray tracing (XPATCH) and full-wave simulation (FEKO). The computed signatures were projected into plan position indicator (PPI) displays, range-Doppler plots, synthetic aperture radar (SAR) imagery and near-field distributions at various frequencies (from HF to X-band) and for typical wind farm configurations. These results were then used to assess offshore wind farm impact on various radar and communications systems.

For the underwater sound, an acoustic source model was developed to predict the sound radiated into shallow water by the vibrations of offshore wind farm towers. Simulations predicting the underwater sound generated by a canonical wind farm (i.e., taking into account nominal farm geometries and bathymetries) were carried out. The source model was coupled to a standard US Navy propagation code for range dependent environments, which enabled simulation of sound propagation beyond the continental shelf and into open ocean. The propagation of sound away from potential wind farm sites off the east coast of the US was simulated using bathymetric data from the ETOPO1 database posted online by the National Oceanic and Atmospheric Administration.

Findings. The stakeholder survey confirmed that mitigation processes are in place to address interference of land-based wind farms on critical land-based radar systems in weather, air traffic control, and long-range surveillance. These processes include mechanisms to evaluate new wind farm proposals (Federal Aviation Administration's obstruction evaluation process, National Telecommunications and Information Administration's clearinghouse for wind energy project, and Department of Defense's energy siting clearinghouse), funded research and development programs to examine various mitigation approaches (e.g., the Interagency Field Test and

Evaluation program), and new software tools under development to better predict impact. The interference from future US offshore wind farms on land-based radar systems can most likely be dealt with using the existing approval mechanisms and technical solutions.

However, offshore wind farms do raise some new concerns for other stakeholders. These new concerns include marine navigation and communications, airborne radar, coastal HF radars, and subsurface acoustics. Under this project, modeling studies were carried out to assess impact and examine potential mitigation methods. Our findings are summarized below.

Potential Interference with Electromagnetic Systems

For *marine navigation*, the effect of offshore wind farms on marine radars installed on boats and shipping vessels was modeled. We used XPATCH and the EREPS model to simulate the electromagnetic scattering and propagation over ocean surfaces. It was found that wind farm scattering could produce a confusing navigational picture if a boat being tracked is inside a wind farm. There would be minimal interference to tracking of vessels operating outside the wind farm. These findings confirm the earlier US Coast Guard determination on the Cape Wind project that “The Coast Guard’s assessment of impact on navigation safety falls within the moderate impact level.” The case when the radar is inside the wind farm was not studied. However, our modeling approach can be extended to cover that scenario. In addition, higher order electromagnetic effects such as multiple scattering between turbines and turbine interaction with the ocean surface were not considered in our PPI simulation and further study is needed to fully characterize their effects.

For sensitive *airborne sensors*, we perform modeling for a generic class of airborne radars onboard aircraft and operating at X-Band under the SAR and ground moving target indictor (GMTI) modes. We developed modeling capabilities for SAR imagery and GMTI range-Doppler chips using XPATCH-simulated signature data. When a wind farm falls within the coverage area of the radar beam, it was found that wind farm scattering could produce serious artifacts in SAR imagery and GMTI range-Doppler chips generated by airborne sensors. This could potentially impact the performance of identification and tracking algorithms. Possible mitigation based on signal filtering was also investigated. It was found that median filtering of the signatures may be a viable approach to mitigate the effect of dynamic wind turbine clutter. Assuming such a mitigation algorithm is properly tested and implemented, the impact on recognition and tracking could be reduced to within an acceptable level.

For *ocean monitoring sensors*, the effect of offshore wind farms on HF radars located on the coast line such as CODAR and WERA systems was modeled. The radar backscattering clutter and forward electromagnetic shadow generated by a typical wind farm in the HF frequency range was simulated using the computer code FEKO. It was found that the overall shadowing effect of a wind farm is not strong and is localized to the region immediately behind the farm from the radar. The strength of the wind farm clutter is estimated to be 18dB below the scattered power from the ocean surface being mapped by the radar. However, the turbine clutter may be comparable to weaker Bragg lines from the ocean surface that are also of interest. Moreover, the turbine clutter will be aliased in Doppler due to the slow PRF (2 or 4Hz) that is typically used in these radars. Mitigation approaches are possible and should be further researched. For example, the combination of range, azimuth and Doppler filtering may be possible to post-process the data to remove turbine clutter.

For *communications systems*, the effect of offshore wind farms on vessel-to-vessel, vessel-to-shore and vessel-to-space links was modeled. We carried out FEKO modeling of the propagation channel when the transmitter or receiver is located within or around a wind farm in order to assess the effect of multipath and shadowing. Given the small degree of the signal fade (<6dB) and the finiteness of the electromagnetic shadow found around wind farms, the effect on communications systems is expected to be low. When more than one turbine is lined up with respect to the transmitter line-of-sight, the fading risk is elevated. The disruption on phase due to wind farms may cause some concerns on those applications where phase information is used, such as direction finding and precise Global Positioning System (GPS) techniques based on carrier phase measurements. These should be further examined.

In summary, our findings for the electromagnetic systems studied are as follows:

(i) Communications systems in the marine environment are unlikely to experience interference as the result of typical wind farm configurations, except under extreme proximity or operating conditions.

(ii) Marine navigation radars and ocean monitoring HF sensors may experience interference under certain proximity and operating conditions as the result of typical wind farm configurations. Pre-deployment investigation is warranted. Mitigation measures may be required.

(iii) Sensitive airborne radars may experience serious interference. However, the degree of interference may be system specific and dependent on whether wind farms are located within the operational area of the radar. Pre-deployment investigation is warranted. Mitigation measures may be required and will need to be further investigated.

Due to the unavailability of system-specific information, it was not possible to carry out an assessment at the system-specific level. Instead, the present modeling effort focused on electromagnetic phenomenology. A more detailed assessment on individual systems may be made by combining the results from our study with detailed system-specific information.

Potential Interference with Underwater Acoustical Sensors

The underwater sound from a single wind turbine exhibits a relatively simple tonal structure, consisting of several frequencies between 100 and 1000 Hz, the amplitudes of which generally decrease with frequency. Local bathymetry and seabed composition determine the rate at which such sound is attenuated as it propagates away from a wind farm. This attenuation rate determines the range at which the sound pressure level is reduced to the ambient noise level. For example, along the continental shelf off the east coast of the US it is anticipated that sound radiated by wind farms located near the coast should usually be reduced to ambient noise levels before it propagates beyond the shelf and into open ocean. In the event that hydrophones or seismic sensors are within the range where sound from the wind farm is above the ambient level, it is anticipated that conventional signal processing such as filtering and beamforming can mitigate the potential interference.

Thus, due to the virtual absence of noise exceeding background levels radiated underwater by wind turbines at frequencies above 1 kHz, interference with underwater acoustical systems is deemed to be unlikely at such frequencies. At frequencies below 1 kHz, the tones radiated by wind turbines may cause interference with certain acoustical systems when placed in close proximity to a wind farm. The definition of "close proximity" depends on many factors, both environmental and specific to the wind farm itself.

Recommendations. First, it is highly recommended that measurement data on electronic systems be collected both before installation and after installation of the new Advanced Technology Demonstration projects funded by the DOE Wind Program. These new facilities, which should become operational between 2015 and 2017, will provide an excellent testing ground to collect in-situ electromagnetic and acoustic data in order to confirm the modeling predictions.

Second, it is recommended that a more complete risk assessment on individual systems be made by combining the results from our study with detailed system-specific information. These are best performed by stakeholders who not only hold such information but have the expertise to make a holistic risk assessment. For underwater acoustics, it is recommended that a future study be conducted that focuses on specific acoustical systems that operate at frequencies below 1 kHz, which was not addressed in the present report. Such a study should include further engagement with stakeholders, including a classified forum in which the Department of Defense may voice its concerns.

Third, it is recommended that research and development into approaches to mitigate the impact of offshore wind farms on electronic systems be initiated through new research funding. The systems to be addressed, in order of their sensitivity to wind farm interference, are: 1) airborne radars operating in high-resolution sensing modes, 2) coastal HF radars, 3) marine radars, and 4) acoustical sensors operating below 1 kHz. For radar systems, particular focus should be placed on low-cost solutions such as those based on signal filtering algorithms or modified navigation practices. In the case of underwater noise, one might investigate possibilities for expanding techniques currently focused on pile driving operations (such as bubble screens, pile sleeves and hydrodynamic sound dampers) to entire wind farm installations.

Fourth, it is recommended that a government working group focusing on the new offshore scenario be established to encourage sharing of information from various agencies and help set protocols for addressing the offshore wind farm interference problem.

Fifth, it is recommended that the development of electromagnetic and acoustic simulation capabilities be continued. Currently, no end-to-end simulation tool exists that can address the various offshore wind farm interference scenarios. An accurate, user-friendly prediction tool will benefit future site-specific assessment tasks. Anomalous propagation effects over the ocean and higher order electromagnetic effects such as those due to multiple scattering, interactions with the ocean surface and non-conducting turbine materials should be further examined.

Sixth, it is recommended that ambient underwater noise measurements be made at potential offshore wind farm sites or, if possible, collected from available databases, and then catalogued for use in future modeling studies aiming to determine acoustical impact.

Seventh, it is recommended that the acoustic source model for underwater noise radiated by submerged wind turbine towers, which was developed under this project, be extended from cylindrically symmetric monopile towers to more complicated but geometrically similar constructions such as tripods, and that a new approach be developed to model noise radiated from floating platforms. Similarly, the implications of new tower constructions should be examined for their above-surface electromagnetic scattering effects.

Introduction

This report was produced on behalf of the Wind and Water Power Technologies Office within Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE), under grant number DE-EE0005380. The award resulted from Funding Opportunity Announcement DE-FOA-0000414, entitled U.S. Offshore Wind: Removing Market Barriers, Topic Area 7: Impact on Electronic Equipment in the Marine Environment.

The objective of this project is to conduct a baseline evaluation of electromagnetic and acoustical challenges to sea surface, subsurface and airborne electronic systems presented by offshore wind farms. The following tasks were carried out during the project: (i) survey electronic systems that can potentially be impacted by large offshore wind farms, and identify impact assessment studies and research and development activities both within and outside the US, (ii) engage key stakeholders to identify their possible concerns and operating requirements, (iii) conduct first-principle simulations on the interactions of electromagnetic signals with, and the radiation of underwater acoustic signals from, offshore wind farms to evaluate the effect of such interactions on electronic systems, and (iv) provide impact assessments, recommend mitigation methods, prioritize future research directions, and disseminate project findings.

The intended audience of this report includes the offshore wind power industry, as well as the radar, sonar and other stakeholder communities who may have concerns on their electronic systems being impacted by offshore wind development.

This report was produced by a team led by the University of Texas at Austin (UT Austin), and included team members from the University of Texas at Austin Applied Research Laboratories (ARL:UT) and Science Applications International Corporation (SAIC). The electromagnetics team comprised the Department of Electrical and Computer Engineering at UT Austin and SAIC. Both groups have extensive experience in radar signature prediction, dynamic clutter modeling and system evaluation. The acoustics team comprised members from ARL:UT, one of the Navy's University Affiliated Research Centers, which conducts mission-oriented research primarily in acoustics, including high-resolution sonar for mine detection, obstacle avoidance, and underwater mapping, and low-frequency sonar for undersea surveillance systems.

This report is organized as follows. Section 1 summarizes our initial survey of electronic systems that can potentially be impacted by large offshore wind farms and our literature review to identify impact assessment studies and research and development activities both within and outside the US. More details of the study are documented in Appendix 1. Section 2 describes our effort to engage key stakeholders and the resulting findings. More details of the study are documented in Appendix 2. Section 3 describes our modeling effort to simulate the interactions of electromagnetic signals with, and the radiation of underwater acoustic signals from, offshore wind farms in order to assess the effect of such interactions on electronic systems. More details of the study are documented in Appendix 3. Section 4 provides our conclusions and recommendations.

Section 1.
Survey of Electronic Systems and Literature on Wind Farm Interference

1.1. Introduction.

Offshore wind energy is a valuable resource that can provide a significant boost to the US renewable energy portfolio. A current constraint to the development of offshore wind farms is the potential for interference to be caused by large wind farms on existing electronic and acoustical equipment for surveillance, navigation and communications.

The interference due to land-based wind farms on radar has already been widely publicized and studied. The rotation of the turbine blades can give rise to strong time-varying radar cross section. The resulting Doppler clutter can interfere with the operation of existing military, aviation and weather radar systems. In 2006, the Department of Defense (DOD) commissioned a study to assess the effect of wind farms on military and air defense radars. For air traffic control, a well-established set of guideline is used by the Federal Aviation Administration (FAA) in the obstruction evaluation process for wind turbines. The effect of wind farms on weather radar has also been carefully addressed by the US National Weather Service. While land-based wind farm studies are valuable, no comprehensive study of the potential for electromagnetic interference has yet taken place in the US for offshore wind farms. This is of course due in large part to the lack of any operating offshore wind farms in the US. In Europe, investigations on the effect of offshore wind farms on marine navigation have been conducted as early as 2004 in the North Hoyle wind farm of the UK and Horns Rev in Denmark.

While there have been many studies of whether airborne noise generated by wind turbines impacts communities, none was found describing how the noise radiated underwater by offshore installations impacts acoustical equipment. The radiated sound pressure levels are relatively low, typically comparable to ambient levels in coastal waters. However, because the frequencies of radiation are so low, below 1000 Hz, sound could potentially propagate to long distances and ultimately into deep water where DOD operations, scientific endeavors such as oceanographic observatories, and commercial interests may be affected. The few measurements that do exist have been taken only in recent years, typically very close to individual wind turbines, and primarily for the purpose of examining the impact on marine mammals. Additionally, apart from use of simple geometrical spreading laws to predict the levels of turbine-generated sound far away from where measurements have been made, modeling of propagation in real ocean environments is only now being reported.

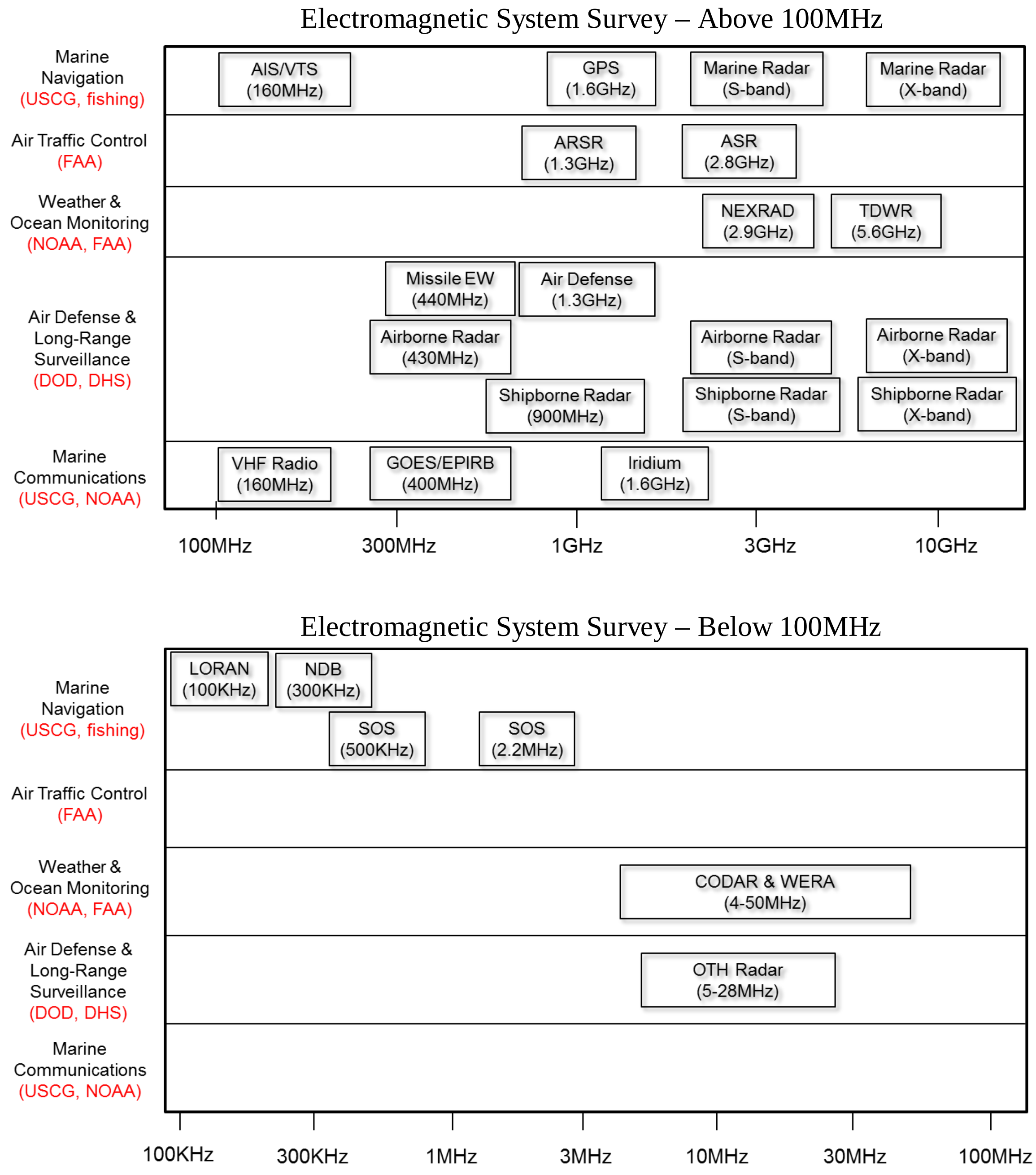
This report sets out to perform a baseline assessment of the potential interference from offshore wind farms to sea surface, subsurface and airborne electronic systems. In this section, we begin with an initial survey of the current landscape in the wind farm interference issue. In Section 1.2, a listing of electronic systems that may be impacted by offshore wind farms in the marine environment is presented. This includes marine navigation equipment, airborne sensors, and subsurface acoustical systems. In Section 1.3, a literature review of wind farm interference research done both within and outside the US is presented. The results of this section enable us to identify the most vulnerable systems to guide the subsequent stakeholder engagement effort in Section 2 and the modeling study in Section 3.

1.2. Survey of Electronic Equipment in the Marine Environment

An initial survey of electronic equipment (marine radar, airborne radar, sonar, navigation and communications equipment) that could potentially be impacted by large offshore wind farms was first carried out. The electromagnetics and acoustics teams each developed a systems list versus frequency and applications/stakeholders.

Fig. 1 shows an overview chart of electromagnetic systems from 100 kHz to 10 GHz versus

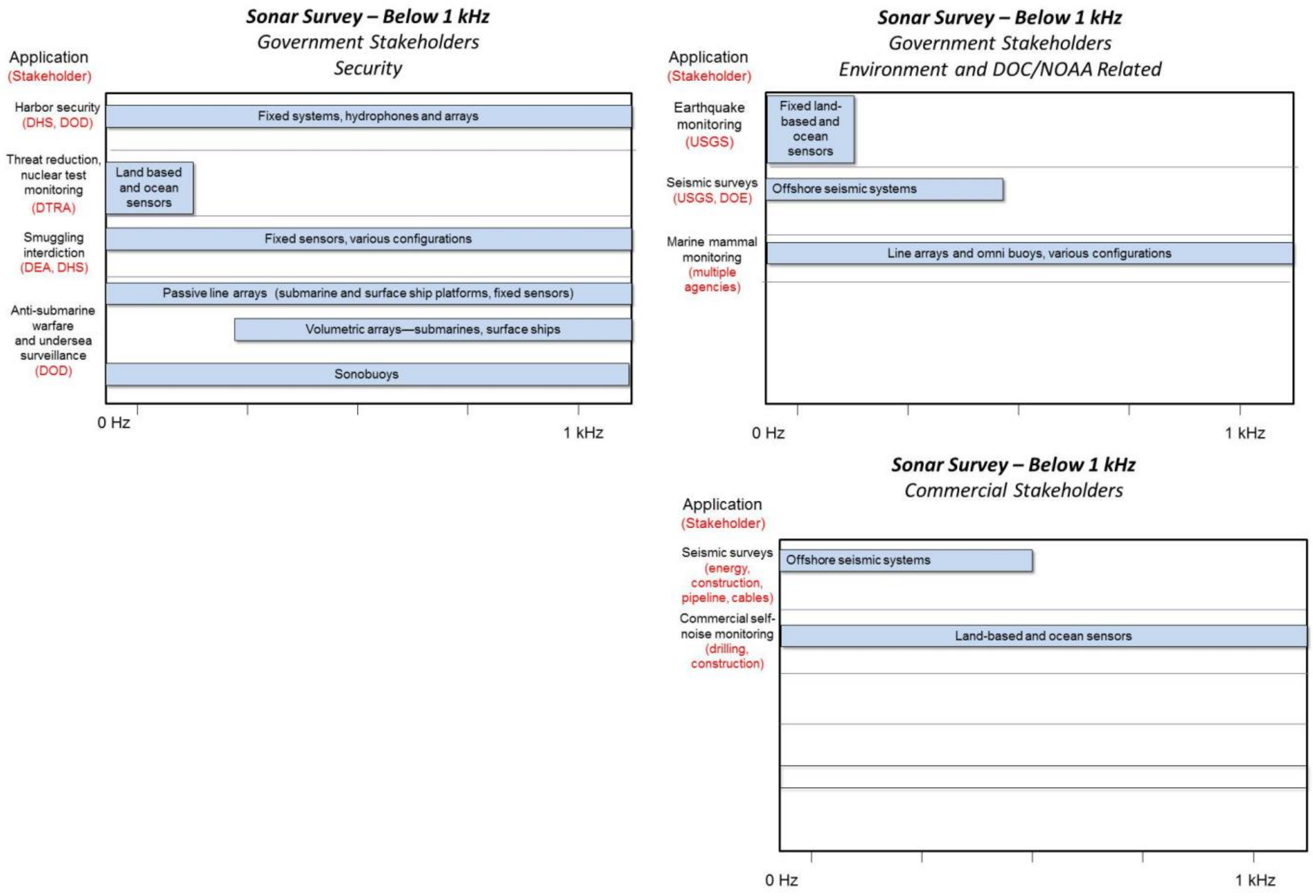
Fig. 1. An overview of electromagnetic systems versus frequency and stakeholders.



frequency band of operation and stakeholders. A more detailed listing of the systems and their key attributes can be found in Appendix A. It can be gathered from Fig. 1 and Appendix A that there are numerous electromagnetic systems operating in the frequency range from 10 kHz to 10 GHz, each with its unique operating characteristics. It would not be feasible to study each system in detail in this initial assessment. Therefore, it is best to categorize and assess the influence of wind farms by frequency bands, as the basic scattering phenomenology is dictated predominantly by operating frequency.

To assist in identifying marine acoustic systems and stakeholders regarding the potential interference from offshore wind turbines, a systematic survey was conducted. Sensors from 0 Hz to 100 kHz were initially identified, along with potential stakeholders. Presented in Fig. 2 are acoustic systems identified below 1 kHz, which is the frequency band relevant to the noise radiated underwater. Additional acoustic systems classified according to the frequency range from 1 kHz to 10 kHz and above 10 kHz may be found in Appendix B.

Fig. 2. An overview of acoustic systems operating below 1 kHz versus frequency and stakeholders.



1.3. Literature Survey of Wind Farm Interference Studies

A review of both US and non-US literature related to wind farm interference on electromagnetic and acoustic systems was conducted. For electromagnetic systems, the literature is grouped into the following areas: marine navigation, air traffic control, weather and ocean monitoring, air defense and long-range surveillance, communications systems, and mitigation techniques. The focus was placed on studies done for the marine environment, although past land-based wind farm studies were also included for completeness. Also, emphasis was placed on more recent studies. The complete reference list can be found in Section 5. In addition, a web site containing all the documents is available for access.

EM-1. Marine Navigation

Investigations on the effect of offshore wind farms on marine navigation have been conducted as early as 2004 in the North Hoyle wind farm of the UK [EM-1.EU1, EM-1.EU2] and Horns Rev in Denmark [EM-1.EU3]. In [EM-1.EU1], measurements were collected on marine radar, communications and positioning systems by QinetiQ and the Maritime and Coastguard Agency. In [EM-1.EU2], helicopter search and rescue trials were carried out. It was found that the effect of wind farms on radar systems is prominent, while those on communications and positioning systems are minor. In [EM-1.EU4], effects of wind farms on marine radar in the Kentish Flats offshore wind farm were investigated extensively. It was found that wind farm induced clutter was clearly visible on radar screens. In [EM-1.EU5], specific guidelines on navigational practices in the vicinity of offshore wind farms were outlined by the UK Maritime and Coastguard Agency. In the US, studies on offshore wind farm effect on marine navigation have focused on the Cape Wind project in Nantucket Sound, MA [EM-1.US1, EM-1.US2, EM-1.US3, EM-1.US4]. These studies have been commissioned by both the developer of Cape Wind [EM-1.US3, EM-1.US4] and the US Coast Guard [EM-1.US1]. In [EM-1.US1], it was shown that wind farm induced clutter on radar screens can be modeled through radar simulation, and the simulations resembled the measurements reported in the Kentish Flats study. Subsequently, the US Coast Guard issued an assessment of "moderate risk" in [EM-1.US2] for the presence of offshore wind farms on marine navigation for Cape Wind.

EM-2. Air Traffic Control

The effect of wind farm clutter on land-based air traffic control (ATC) radar has been well studied in both Europe and the US, since it raises serious safety concerns. Both flight trials [EM-2.EU1] and detailed analysis [EM-2.EU2] have been carried out in the UK to assess wind farm interference on ATC radars. Specific guidelines on how to assess the potential impact of wind farms on ATC radars were issued in [EM-2.EU3]. In the US, the guideline set by [EM-2.US3], which adopts a similar set of methodologies set forth in [EM-2.EU3], is used in the obstruction evaluation process for wind turbines. The question of potential interference from offshore wind farms on ATC radar was raised in the Cape Wind project. In [EM-2.US1], FAA performed a study to address this issue using existing modeling tools for land-based wind farms [EM-2.US2].

EM-3. Weather and Ocean Monitoring

The effect of wind farms on weather radar has been carefully addressed by the US National Weather Service, which operates 159 NEXRAD systems [EM-3.US1, EM-3.US2, EM-3.US3, EM-3.US4]. Specific observations of the wind farm phenomenology were conducted in [EM-

3.US4, EM-3.US5]. Since wind farms can create Doppler clutter that contaminates data products from weather radar, guidelines on impact zones were set up in [EM-3.US2, EM-3.US3]. In particular, distances within 3km from the radar and distances up to 18km were designated as severe impact and significant impact zones, respectively. For future offshore wind farms, these distances may need to be updated to account for the larger size of offshore wind turbines [EM-3.US3]. In Europe, the Operational Programme for the Exchange of Weather Radar Information (OPERA) group has studied and published a set of guidelines for weather radar [EM-3.EU1, EM-3.EU2].

The potential impact of offshore wind farms on ocean monitoring radars operating in the HF frequency range has recently received some attention. In [EM-3.EU3], wind farm clutter from the Rhyl-Flats offshore farm in UK's Liverpool Bay was reported on the WERA (Wave Radar) system, which operates at 13MHz. Of particular interest is the availability of measured data both before and after the operation of the farm. In [EM-3.US6], a simulation study was conducted on the CODAR (Coastal Ocean Dynamics Applications Radar) system by CODAR Ocean Sensors Ltd. to assess potential interference. [EM-3.EU4] is the conference proceedings from the 60th Topical Expert meeting with participation from 20 countries in Europe, US and Asia. It contains recent R&D activities to address wind farm interference on radar and radio links.

EM-4. Air Defense and Long-Range Surveillance

The effect of wind farms on air defense radar has been a topic of strong concern in Europe. Several flight trials were conducted by the UK Royal Air Force in 2005 [EM-4.EU1, EM-4.EU2]. As a result of the trials, it was recommended that any wind farm that comes within the radar line of sight of an air defense radar, regardless of range, be closely examined. In the US, the potential impact of wind farms on the military was assessed in the 2006 Department of Defense report [EM-4.US1]. Complementing the report were measurement data collection on a land-based wind farm in Fenner, NY [EM-4.US2] and corresponding electromagnetic simulations done using high-frequency ray tracing [EM-4.US3, EM-4.US4] in order to establish a database of wind turbine signatures. A number of flight trials on the ARSR-4 long-range surveillance radar have also been carried out by the Air Force 84th Radar Evaluation Squadron, with the most recent campaign reported in [EM-4.US5, EM-4.US6]. It was found that wind farms lead to reduced probability of detection and increased false targets. The impact of wind farms on the missile defense early warning radars were assessed in [EM-4.US7]. No open literature was found on wind farm interference with airborne radars.

EM-5. Communications Systems

The potential impact of wind turbines on television transmission was investigated as early as the late 1970s by Sengupta and Senior [EM-5.US1, EM-5.US2]. Similar studies have also been carried out in Europe [EM-5.EU1, EM-5.EU2]. More recently, VHF radio operation was tested during the construction phase of the Horns Rev offshore wind farm in Denmark [EM-5.EU3]. No observable effects were reported. Detailed studies were carried out on communications and navigation equipment in the North Hoyle farm in the UK [EM-5.EU4, EM-5.EU5]. The effect of wind farms on radio communication and digital television in the UHF band was addressed by simulation and measurement in [EM-5.EU6, EM-5.EU7]. Similar studies have also been reported in Canada [EM-5.CA1] and New Zealand [EM-5.NZ1]. To date, the effects due to wind farms on radio and television communications systems have not been found to be very significant in comparison to those observed in radar systems.

EM-6. Mitigation Techniques

A number of ideas for mitigating the effects of wind farms on radar have been proposed and explored. These ideas can be divided into three groups. 1) From the operational perspective, mitigation approaches include rerouting of aircraft and ships around the wind farm and providing training to radar operators to distinguish wind farm clutter from real targets. 2) From the wind farm developer's perspective, possible mitigation methods include using terrain screening to mask wind farms from radar, developing and deploying stealthy turbines, and properly designing wind farm layout to minimize wind farm clutter seen by the radar. 3) From the radar perspective, mitigation approaches include relocating the radar, optimizing radar parameters to minimize wind farm interference, upgrading radar hardware, using advanced processing/filtering techniques, and using gap filler radars to cover regions blocked by wind farms. These options are examined and discussed in [EM-6.EU1, EM-6.EU2, EM-6.US1, EM-6.US2]. In [EM-6.US3, EM-6.US4], radar hardware and software processing techniques are discussed for air traffic control and long-range surveillance radars. In [EM-6.US5, EM-6.EU3, EM-6.EU4], R&D activities in the US and Europe into stealthy turbines are reported. In [EM-6.EU5], the feasibility of using in-fill radar in UK's Greater Wash area is examined.

In summary, electromagnetic interferences from both land-based and offshore wind farms have been studied in Europe. In particular, a number of systems have been fairly well characterized in-situ in offshore wind farms. In the US, significant efforts have already taken place to address electromagnetic interference from land-based wind farms. For offshore wind farms, only limited modeling studies have been done. No comprehensive baseline assessment is available. Nor has measurement data collection been possible due to the lack of any operating offshore wind farms.

For **underwater acoustic** systems, the literature is grouped into the following areas: noise measurements, impact on marine mammals, impact on fish/fisheries, and mitigation techniques. The complete reference list can be found in Section 5. In addition, a web site containing all the documents is available for access.

UA-1. Noise Measurements

Currently all offshore wind farms reside outside the US, and the vast majority of underwater noise studies of operational wind farms were made in Europe. Two studies that stand out due to their thoroughness are a 2003 report on the Utgrunden wind farm off the east coast of Sweden [UA-1.EU1], and a 2006 report on the Horns Rev wind farm off the west coast of Denmark [UA-1.EU2]. The Utgrunden wind farm consists of only 7 turbines, and its location, local bathymetry, etc., are well described in the report. The Horns Rev wind farm possesses 80 turbines. The two reports show similar low-frequency noise spectra from individual turbines, which are characterized by a tonal structure associated with gear noise. The fundamental tone is typically between 150 and 200 Hz and has a sound pressure level less than 125 dB (re 1 μPa) at 100 m, with a few higher harmonics at lower sound pressure levels. There is no indication of significant (or even measurable at 100 m) wind turbine noise above 1 kHz. Several authors have summarized noise measurements made on a number of other wind farms [e.g., UA-1.EU3], and the noise spectra look much the same.

One very recent (2013) US report is of particular significance, titled "Acoustic Noise and Electromagnetic Study in Support of the Rhode Island Ocean SAMP" (Special Area Management Plan), because it focuses on "the environmental impact of an offshore wind farm consisting of 8 turbines in an area south of Block Island, Rhode Island" [UA-1.US4]. In particular, the report discusses "the underwater acoustic noise generated by the various phases of the life cycle of a wind farm from site surveys, construction, operation, and decommissioning." Background noise levels were measured on site, and anticipated underwater noise from operational wind turbines was simulated based on measurements made at the Utgrunden offshore wind farm in Sweden [UA-1.EU1]. While the impact on acoustical systems was not considered, "The modeling suggests that the 8 turbine wind farm would have little impact on marine life." At a distance 10 km south of the proposed site, and assuming "that the [eight] turbines are operating at the highest possible power setting for the wind conditions", it was determined that "additional noise from the wind turbines is significantly less than noise from shipping, wind and rain for the period covered by these measurements (5 weeks in October and November, 2008)."

Measurements of underwater noise due to pile driving are relevant to the future construction, even if not operation, of wind turbines in US coastal waters. A typical recent study reports measurements of pile driving in water of depth 25 ft performed during the Washington State Ferries 2006 Test Pile project, with and without three different noise abatement systems implemented: bubble screen, foam-walled steel pile, and double-walled steel pile [UA-1.US3]. However, other than the similarities to wind turbines in terms of shallow water and noise abatement, the frequencies and sound pressure levels are much higher than those generated underwater by operational wind farms. The present report focuses only on operating wind farms, not their construction.

A determination of whether the underwater noise from wind farms impacts acoustical systems ultimately depends on signal-to-noise ratios and therefore ambient noise levels. To this day, the largest compilation of ambient ocean noise measurements reported in the open literature was published in 1984 [UA-1.US1]. A 2003 National Research Council report on ocean noise and marine mammals calls attention to this paucity of ambient noise data [UA-1.US2]. The report notes one particularly large collection of noise data compiled by the Naval Oceanographic Office (NAVOCEANO) for the US Navy, but points out that "Access to the databases listed is restricted, making it difficult to review them and use them for scientific purposes."

UA-2. Impact on Marine Mammals

The most extensive studies of underwater sound radiation from operational offshore wind turbines have been in connection with potential impacts on marine mammals, and the majority of these studies have been performed in Europe. For example, recordings of underwater noise from three different types of wind turbines in Denmark and Sweden (Middelgrunden, Vindeby, and Bockstigen-Valar) during normal operation as reported in 2009 [UA-2.EU5] revealed that the radiated noise exceeded background levels only at frequencies below 500 Hz. While porpoises and seals might exhibit behavioral reactions to the noise at close range, "the noise is considered incapable of masking acoustic communication" by these mammals [UA-2.EU5]. Although the impact of noise radiated by pile driving during construction of offshore wind farms on marine mammals may be significant [UA-2.EU1, UA-2.EU3], earlier studies [UA-2.EU2, UA-2.EU4] reinforce the conclusion [UA-2.EU5] that the low-level, low-frequency underwater sound radiated by operational wind farms is anticipated to have minimal impact on marine mammals.

A 2003 report by the National Research Council [UA-2.US1] titled "Ocean Noise and Marine Mammals, and a 2009 report to Congress prepared by DOE on potential environmental impact of offshore energy technologies [UA-2.US2], should also be consulted for reviews of studies concerned with marine mammals.

UA-3. Impact on Fish/Fisheries

As in studies of effects of anthropogenic (human-made) sound on marine mammals, the sources of underwater noise related to offshore wind farms that are likely to have the greatest effects on fish concern impact noise due to pile driving during construction of the farms, rather than the tonal noise radiated during operation of the turbines. Even so, one extensive examination of "both the peer-reviewed and 'grey' literature" by two prominent experts on bioacoustics led them to conclude that "very little is known about effects of pile driving and other anthropogenic sounds on fishes, and that it is not yet possible to extrapolate from one experiment to other signal parameters of the same sound, to other types of sounds, to other effects, or to other species." [UA-3.US1]

One European study [UA-3.EU1] set out to investigate the claim made by a commercial fisherman that certain fish do not migrate between the towers in the Vindeby Offshore Wind Farm off the coast of Denmark when it is windy. The claim was based on the fisherman's catch at different locations around the wind farm. Underwater noise, among other phenomena, was investigated using measurements close to the towers (14 m). Results of this study were inconclusive. More recently [UA-3.EU2], in studies of the Lillgrund wind farm off the coast of Sweden it was concluded that "In close vicinity (less than 10 m) to a turbine the received level (about 119 to 136 dB re 1 μPa for the 127 Hz component) are most likely sufficient to evoke a behavioural reaction in some species like cod", but that "It is only within a few meters of the foundations that the noise is at a level that could cause significant behavioural reactions as shown in aquaria and field studies."

UA-4. Mitigation Techniques

The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety [UA-4.EU2] has identified as potential methods of reducing underwater noise radiated from offshore wind turbines the following mitigation techniques, prototypes of which have been demonstrated: bubble screens, pile sleeves, hydrodynamic sound dampers, BEKA jacket, ring of fire hoses, cofferdam, gravity foundation, and suction bucket. A DOE report prepared for Congress [UA-4.US5] adds several mitigation techniques to this list that are specific to pile driving operations during the construction phase. Considerable attention has been devoted to bubble screens because of cost and relative ease of implementation [UA-4.US1, UA-4.US2, UA-4.US3, UA-4.US4, UA-4.EU1]. A modeling study of pile driving noise in shallow water (15 m to 30 m depth) [UA-4.US6], based on analytical and numerical techniques similar to those described in Appendix C2, led to conclusions that bubble screens and compliant surface treatments reduce noise levels by approximately 10 dB, compared with massive dewatered cofferdams that reduce noise levels by approximately 20 dB. These aforementioned applications of bubble screens to noise abatement have relied either on the principal of acoustic impedance mismatch between gas and water, or the mass-spring resonance produced by the compliance of a bubble layer and the mass loading of the surrounding water. Very recently it has been demonstrated in lake experiments that exploiting bubble resonances and the associated losses can reduce noise levels by more than 40 dB at frequencies of several hundred Hz radiated from sound sources near the water surface, and not in contact with the bottom [UA-4.US7].

In summary, the vast majority of studies of underwater sound radiation by operational offshore wind farms have been performed in Europe and primarily for the purpose of assessing the impact of the radiated noise on marine mammals. These studies are pertinent to the present one insofar as they report measurements of the radiated noise that permit calibration of acoustic field models developed to estimate potential impact at anticipated locations of offshore wind farms in the US. No studies of how underwater sound affects acoustical equipment and systems were identified. Mitigation techniques including bubble screens, pile sleeves, hydrodynamic sound dampers, BEKA jacket, ring of fire hoses, cofferdam, gravity foundation, and suction bucket have been tested and demonstrated varying degrees of success.

Section 2.
Engagement with Key Stakeholders

2.1. Introduction.

The project team set out to engage several key stakeholders in government and industry to identify concerns on interference from offshore wind farms, characterize potential impact to operations, determine known requirements and options for mitigation, and establish future research needs. Personal interviews with stakeholders were conducted for both electromagnetic and acoustic systems. Through this process, key technical issues were identified and addressed in the subsequent modeling study. Section 2.2 summarizes the stakeholder interview effort and findings for electromagnetic systems. Section 2.3 summarizes the effort and findings for acoustics systems. Details on the methodology employed, the list of participants, the set of interview guiding questions, and the responses are documented in Appendix B.

2.2. Electromagnetic Stakeholder Interviews.

In-depth personal interview was chosen as the appropriate research approach to gather technical information and opinions on the subject matter from a wide range of stakeholders. Interviews were carried out to understand past experiences with land-based wind farm interference and potential concerns with future offshore wind farms on various systems operated by the stakeholders. A set of guiding questions were developed, pretested, and refined for this purpose.

Initially, a pool of candidates was gathered with the help of DOE and a DOE-hired consultant. They included personnel from the Department of Defense (DOD), Federal Aviation Administration (FAA), United States Coast Guard (USCG), National Ocean and Atmospheric Administration (NOAA) and the Department of Homeland Security (DHS). These candidates were first contacted via e-mail to request their participation in our study. The participant pool then expanded via snowball sampling, with the goal to cover as many stakeholder groups as possible. It should be noted that since participation is voluntary, not all identified stakeholders agreed to the interview. This could be due to the sensitive nature of their systems for national security.

Those who agreed to participate were contacted to arrange a phone interview. All interviews were semi-structured, with broad and open-ended questions to allow for a more stakeholder-centric view from the interviewees. The interviews were conducted over two-and-half months during the summer of 2012. On average, each interview lasted about 40 minutes. Some of the interviews were conducted with more than one individual from a stakeholder group during the call. All but one interview were conducted over the phone. Immediately after each interview, key notes taken were summarized into written form.

During the first part of the interview, stakeholders were asked to comment on the effect of existing land based wind farms on their systems.

It is confirmed that land-based wind farms do interfere with a number of high-priority radar systems including air traffic control radar (ASR-11), long-range surveillance radar for air defense (ARSR-4, CARSR), and weather radar (NEXRAD). In addition, sensitive test and evaluation sites that may require a pristine electromagnetic environment for testing may be impacted. On the other hand, communications systems are usually a lesser concern, as very few cases on interference have been reported.

The types of interference observed can be categorized into several effects. The most insidious effect is the reduction in the probability of detection for radar in the vicinity of wind farms due to raised clutter level. In addition, false targets are generated due to Doppler returns from the rotating blades. Finally, at very close range, there is beam blockage from tightly spaced wind turbines.

Several measures are being taken for handling wind farm interference. First, various technical mitigation approaches are currently being investigated and tested. These include radar parameter optimization to deal with turbine clutter, dual beam processing, and in-fill radars. An interagency field test and evaluation (IFT&E) group has been established jointly by DOE, DOD, DHS and FAA to assess the various mitigation capabilities provided by industry. In addition, protocols to evaluate future wind farm proposals are in place. These include FAA's obstruction evaluation process, National Telecommunications and Information Administration's (NTIA's) clearinghouse, and DOD's energy siting clearinghouse. They provide the mechanisms for government agencies to make technical determinations on newly proposed wind projects, which can be quickly fed back to wind developers. Lastly, new simulation tools are being developed to better predict the effects of wind farms on various radar systems.

During the second part of the interview, stakeholders were asked to comment on the potential effect of future offshore wind farms on their systems.

Some stakeholders believe that most of the existing experience on land-based wind farms can be directly translated to offshore wind farms for their systems. In particular, land-based radar systems for air traffic control, air defense and weather that have coverage into coastal waters may experience interference from offshore wind farms that is similar to interference due to land-based wind farms. The main difference is expected to come from the larger size of offshore turbines, which will result in stronger radar scattering. In addition, anomalous propagation effects over the ocean and interactions between the turbine and sea surface may give rise to additional phenomenology, but the true effect is unknown at this moment. These stakeholders also believe that most of the mitigation strategies currently being investigated for land-based wind farms can likely be transported over to offshore wind farms. The Bureau of Ocean Energy Management (BOEM) has set up a procedure for conducting assessment for leasing blocks over federal waters. The effect of offshore wind farms on air traffic control and long-range surveillance radars are being considered in this process. Over 2,000 leasing blocks on the East Coast have been assessed thus far.

For other stakeholders, offshore wind farms do raise some new concerns. One important concern is marine navigation. The impact of offshore wind farms on marine navigation had been conducted through field trials in Europe. However, such opportunity does not yet exist in the US. USCG has been involved with the evaluation of the Cape Wind project on marine navigation, and contracted Technology Services Corporation (TSC) for a modeling study to assess its effect on marine radar. A comprehensive study on the various navigation, radar and communications systems on-board a ship is still needed. In addition, a closer examination of the guidelines for vessels to navigate around wind farms is desired.

For airborne radar systems, which have a greater footprint than land-based radar systems, the degree of impact from wind farms may be different from that experienced by land-based radar systems. In addition, some of these sensors have high-resolution imaging capabilities. They depend on sophisticated processing algorithms such as Synthetic Aperture Radar (SAR) and Ground Moving Target Indicator (GMTI), which may be more susceptible to dynamic wind farm clutter.

A network of HF radar sensors (CODAR and WERA systems) is operated by NOAA for large-area ocean surface current monitoring out to 250km off the US coast. These systems are located along the coastline, and may be impacted by offshore wind farms. Some preliminary measurement data have been collected in Europe on the WERA system. However, no data is available for the US network.

In addition to their potential impact on radar systems, offshore wind farm structures may also affect communications systems operating in the marine environment. This includes vessel-to-vessel, vessel-to-shore and vessel-to-space links. Examples of systems that potentially may be affected include satellite links such as GPS (global positioning system) for navigation and Iridium and GOES for data relay, VHF radio for marine communications, and AIS (automatic identification system) for vessel tracking.

Our key findings from the stakeholder interviews can therefore be summarized as follows.

The interference from land-based wind farms on land-based radar systems has been widely observed and is considered well understood. Mitigation processes are either already in place or being put in place to deal with such interference. The interference from future US offshore wind farms on critical land-based radar systems can most likely be dealt with using the existing processes. However, the interference from offshore wind farms on marine and airborne electronic systems should be further researched and assessed through simulation and measurement studies.

2.3. Acoustics Stakeholder Interviews.

As with the stakeholders in electromagnetics, personal interviews were chosen as the method for gathering technical information and opinions from stakeholders on the potential impact of underwater noise from operational offshore wind farms on electronic systems used underwater.

Initial contacts were made by email, with a list of talking points in the form of an attached questionnaire. In the electromagnetics interviews covered in Sec. 2.2, some stakeholders could extrapolate their experiences with land-based wind farm interference to offshore wind farms. However, such extrapolation is impossible in the case of potential interference from underwater sound. The primary source of the airborne noise is aerodynamic in nature. The noise is broadband in the range of audibility and it is generated by turbulent airflow over the blades.

Infrasound (below the hearing range) on the order of 1 Hz is also generated due to time-varying structural loads associated with water waves, wind fluctuations, and rotational imbalances in the rotor dynamics. In contrast, the source of the noise radiated underwater is due to mechanical vibrations emanating from the gearbox that propagate down the tower and into the water. The

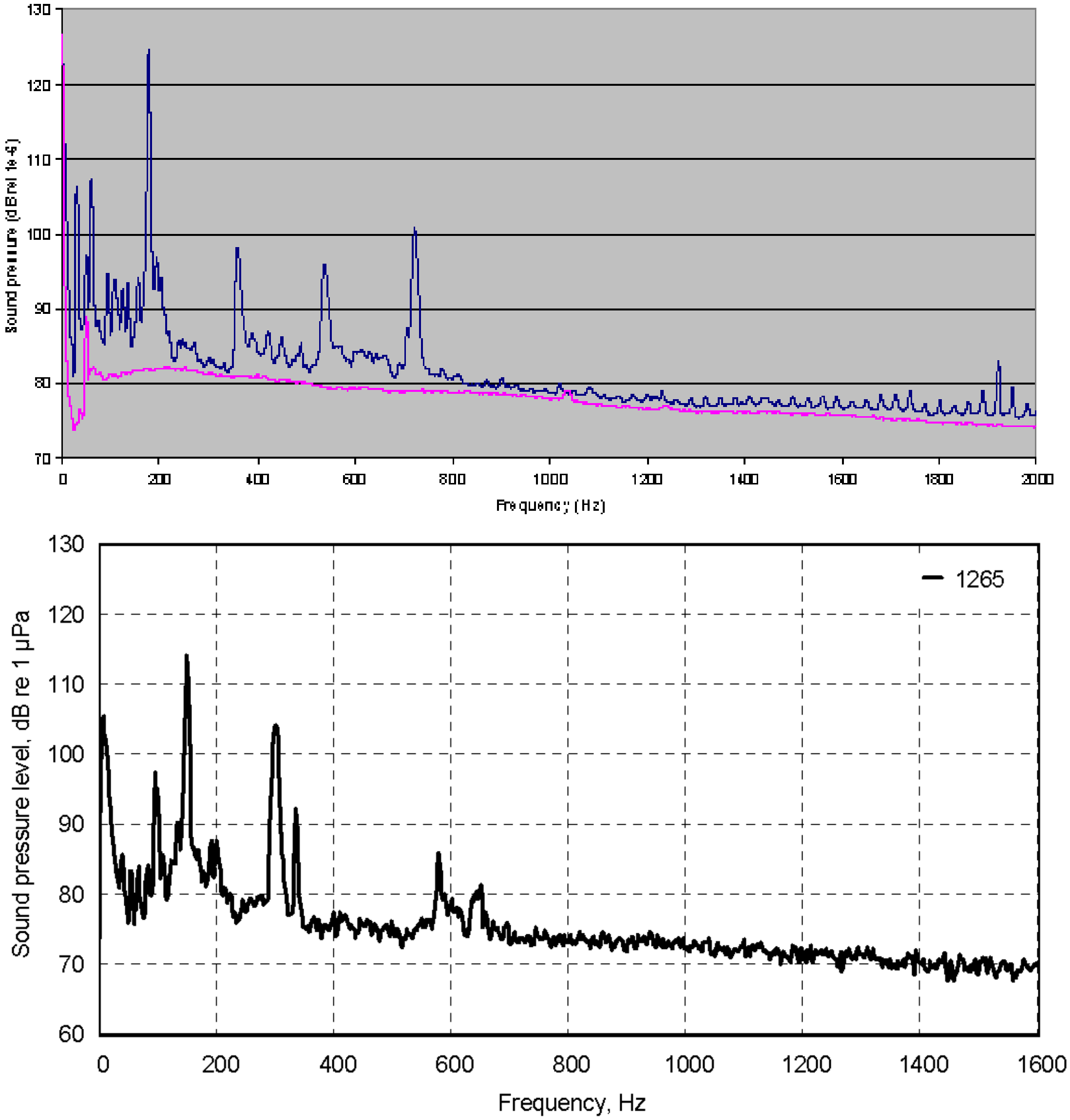


Fig. 3. Typical underwater noise spectra radiated from a single wind turbine at (above, blue curve) the Utgrunden wind farm off the east coast of Sweden [UA-1.EU1, 2003] and (below) the Horns Rev wind farm off the west coast of Denmark [UA-1.EU2, 2006].The Utgrunden measurements were made in water 18 m deep with a hydrophone positioned 1 m above the sea floor and 83 m away from a turbine operating in wind with speed 14 m/s. The Horns Rev measurements were made in water having depth varying between 6 and 14 m (exact depth is not provided in the report; this range of depths is reported in general information about Horns Rev provided elsewhere) with a hydrophone positioned 2.5 m above the sea floor and 87 m away from a turbine operating in wind with speed 12 m/s. The text in the vertical axis labels should read “dB re 1 µPa/√Hz”.

resulting noise is dominated by several harmonically related tones beginning typically at a fundamental frequency between 100 and 200 Hz. No significant underwater noise from operational offshore wind farms, and especially no tonal components, have been measured above 1000 Hz. Typical measured frequency spectra are presented in Fig. 3, the upper spectrum (blue curve) from a single wind turbine in the Utgrunden wind farm off the east coast of Sweden [UA-1.EU1], and the lower spectrum from a single wind turbine in the Horns Rev wind farm off the west coast of Denmark [UA-1.EU2]. These spectra provide context for the stakeholder feedback that follows.

Only feedback from stakeholders employing electronic systems that operate at frequencies in the neighborhood of 1000 Hz or below is reported in this section. Brief discussion of feedback related to electronic systems that operate well above 1000 Hz is reported in Appendix B, e.g., mine warfare (above 20 kHz), commercial fishing (above 30 kHz), and swimmer detection (above 80 kHz). For example, fish-finder sonar systems operate at frequencies upwards of 30 kHz and would not experience any interference from wind turbine noise.

By far the largest stakeholder in terms of potential impact of underwater sound sources on electronic systems that incorporate acoustic sensors is the US Navy. A teleconference was held at which Navy representatives provided guidance on points of contact for assessing potential impact on electronic systems for both electromagnetics and acoustics. At the request of the Navy, the reports from which the noise spectra in Fig. 3 were reproduced, together with the questionnaire, were sent to the designated point of contact for acoustics. For all but two questions the Navy replied that they were unable to comment due to security concerns. In response to the question “In your experience, have any of your sensors or systems been adversely affected by background noise from any source at frequencies below 2 kHz?” they replied that the effect is unknown because the Navy currently possesses no empirical data to suggest that their systems have been affected. In response to the question “Do you have any concerns that future stakeholder systems may be affected by wind turbine generated noise?” they replied that based on the frequency range, their systems may be affected by wind turbine generated noise. The impact on Navy systems is thus inconclusive.

The Office of Naval Research was also contacted. The consensus view of several program managers was that ONR has flexibility in choosing locations for testing and evaluating emerging technologies, and they can select areas for performing sea tests where background noise underwater from offshore wind farms will not be a problem.

Sub-bottom profiling in the ocean makes use of sonar directed downward. It may be towed behind a research vessel or hull mounted, and it is used to create vertical profiles of the sea floor and map sediment layers to depths of 10 to 100 m below the sea floor. Since sub-bottom profilers use frequencies starting near 1000 Hz and above, and they possess vertical directionality, an in-house expert on this technology at ARL:UT believes that underwater noise radiated by offshore wind farms is unlikely to interfere with sub-bottom profilers.

Marine seismic surveys for oil and gas exploration, as well in general geophysics applications, are distinguished from sub-bottom profiling of sediment layers by their penetration to much greater depths beneath the ocean floor. As a result, lower frequencies, below 1000 Hz (typically below 500 Hz) are used because of the smaller propagation losses. Stakeholder replies were obtained from Schlumberger, ION GeoVentures, and the Institute for Geophysics at UT Austin. These representatives of the oil and gas exploration community are interested in knowing where future offshore wind farms are likely to be built and what their likely spectral characteristics and noise levels versus frequency will be. In geophysics applications, seismic signals below 20 Hz are frequently used. While there may be wind farm noise in certain frequency bands of interest to seismologists, it is anticipated that mitigation using standard signal processing and beamforming likely will be effective, or that other noise sources will dominate the contribution due to wind turbines.

Both Department of Homeland Security and DOD are interested in monitoring maritime traffic using underwater acoustics. Here the frequency range of interest is 10 Hz to 25 kHz, where both narrowband noise (e.g., tonal in nature) and broadband noise are monitored for this purpose. An in-house expert on this technology at ARL:UT believes that existing signal processing and beamforming in acoustic marine traffic monitoring systems is expected to provide sufficient mitigation of potentially interfering signals radiated underwater by offshore wind turbines.

The monitoring of marine mammals is of interest to industry, defense, and academia. Whales and porpoises are monitored by detecting frequencies that range from 500 Hz to nearly 100 kHz. Therefore depending upon proximity of wind farms to the sensors, noise from wind farms may interfere with the signals of interest. Acoustic sensors used by academic groups (University of New Orleans, University of Southern Mississippi, and University of Texas) are normally deployed in deep water, on the order of 1000 m, and therefore far from likely locations of offshore wind farms in coastal waters.

Section 3.
Assessment Based on First-Principle Modeling

3.1. Introduction.

The project team set out to provide a baseline assessment of the potential impact of offshore wind farms on electronic systems based on first-principle electromagnetic and acoustic modeling. In Section 1 of this report, electronics systems typically encountered in sea surface operations, airborne missions, and sub-surface operations were first identified. Subsequently in Section 2, detailed personal interviews with key stakeholders were conducted to identify the full range of concerns on the effect of offshore wind farms on these systems. In this section, we first select those systems that are potentially most susceptible to offshore wind farm interference, yet have been least studied thus far. This ensures that we devote our modeling resources to the most important issues, while not duplicating past or ongoing efforts in this area.

The electromagnetic modeling effort focused on several key cases identified through our literature survey and stakeholder interviews. These cases include marine radar, airborne radar, HF radar, and communications systems. Electromagnetic modeling of utility-scale, horizontal-axis wind turbines was carried out. Modeling results for wind farm interference were generated in the form of plan position indicator (PPI) displays, range-Doppler plots, SAR imagery and near-field distributions at various frequencies (from HF to X-band) and for typical wind farm configurations. These results were then used to assess offshore wind farm impact on various radar and communications systems.

For the underwater noise, an acoustic source model was developed to predict the sound radiated into shallow water by the vibrations of offshore wind farm towers. This model was extended to predict the underwater sound fields generated by arrays of vibrating offshore wind farm towers. Simulations predicting the underwater noise generated by a canonical wind farm (i.e., taking into account nominal farm geometries and bathymetries) were carried out. In addition, coupling the acoustic source model to a standard US Navy propagation code for range dependent environments, and making use of bathymetric data from the ETOPO1 database posted online by NOAA, enabled simulation of sound propagation over potential wind farm sites on the eastern seaboard of the US. Simulations for four potential wind farm locations in the mid-Atlantic region were performed and analyzed using sediment loss factors for three canonical types of seabed.

Section 3.2 summarizes our modeling effort in electromagnetic systems. Section 3.3 summarizes our modeling effort in acoustics systems. Details on the modeling approach and the modeling results can be found in Appendix C.

3.2. Electromagnetic Modeling Study.

Four cases were studied using electromagnetic modeling: marine radar, airborne radar, HF radar, and communications systems. It is worthwhile to point out that there are other critical systems of concern (long-range surveillance, air traffic control and weather radars). However, currently there are other efforts to address these systems, and they are therefore outside the scope of our modeling study. Below, detailed descriptions of the four case studies are reported.

Marine Radar: This study was performed to simulate the effect of offshore wind farms on marine radars installed on boats and shipping vessels. The radars considered are commonly installed systems operating in the S- and X-band frequencies. Modeling was performed for a generic class of radars operating in these bands. Although no vendor-specific radar processing was performed, the modeling data should provide representative results for a baseline assessment.

For this case study we developed a radar model to simulate the dynamic scattering from wind farms. We used Xpatch and the EREPS model to simulate the electromagnetic scattering and propagation over ocean surfaces. We validated the Xpatch simulation using measurement data from the 2006 Air Force Research Laboratory (AFRL) wind turbine collection. The validation showed reasonable comparison between Xpatch and measurements. In addition we validated the dynamic Doppler prediction capability by comparing to AFRL measured spectrograms. The Doppler predictions also showed reasonable comparison to the AFRL measurements. We simulated the corresponding PPI display as seen on marine radars at X-band and S-band. We simulated two scenarios that typical vessel operators would encounter while navigating within and around the wind farm (see Fig. 4). The first scenario was that documented in the 2008 TSC report for the proposed Cape Wind project. Our PPI display simulations showed good comparison to those reported by TSC. The wind farm configuration in the second scenario was provided by DOE and was primarily used to draw conclusions for this study. The PPI display showed that the wind farm is visible on the PPI display of vessel radar operators. Boats can be detected and tracked unobstructed outside the wind farm. However, the wind farm is a

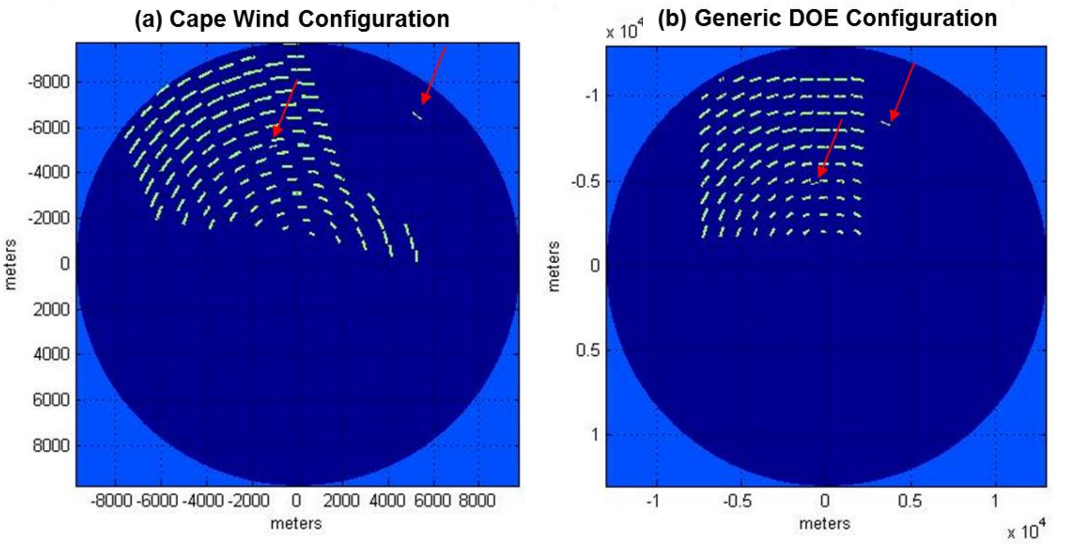


Fig. 4. Simulated PPI displays containing wind turbines and boats as seen on an S-band (3 GHz) marine radar. The red arrows mark the positions of the two boats. (a) The proposed Cape Wind configuration. (b) A generic 10x10 wind farm configuration provided by DOE.

prominent target for the radar operator, and made detection and tracking of boats within the farm more difficult.

Based on this study, we make the following assessments and recommendations:

1) Wind farm scattering could produce a confusing navigational picture when the boat being tracked is inside a wind farm.
2) There would be minimal interference to tracking of vessels operating outside the wind farm. Though we did not study the case when the radar is inside the wind farm, this modeling approach can be extended to cover that scenario in future studies.
3) This study confirms the earlier USCG determination on the Cape Wind project that "The Coast Guard assessment of impact on navigation safety falls within the moderate impact level."
4) Field measurements are needed to corroborate the modeling results. The next phase of DOE offshore wind projects may provide a good testing ground to collect marine radar data.
5) Higher order electromagnetic effects were not considered in our PPI simulation and further study is needed to fully characterize their effects.

Airborne Radar: DOD operates a number of airborne sensors. Some have high-resolution imaging capabilities, which depend on sophisticated processing algorithms such as synthetic aperture radar (SAR), inverse SAR (ISAR) and ground moving target indicator (GMTI). This study was performed to model the effect of wind farms on radars installed on airborne platforms. Detailed information on these sensors was not available to us. The evaluation was performed for a generic class of radars operating at X-Band under the SAR and GMTI modes.

For this case study we developed a radar model to simulate the dynamic scattering from offshore wind farms for the types of sensors (SAR and GMTI) that typical airborne platforms would operate in coastal waters. We developed a SAR and GMTI modeling capability using Xpatch-simulated signature data. We simulated a scenario that a typical airborne sensor would

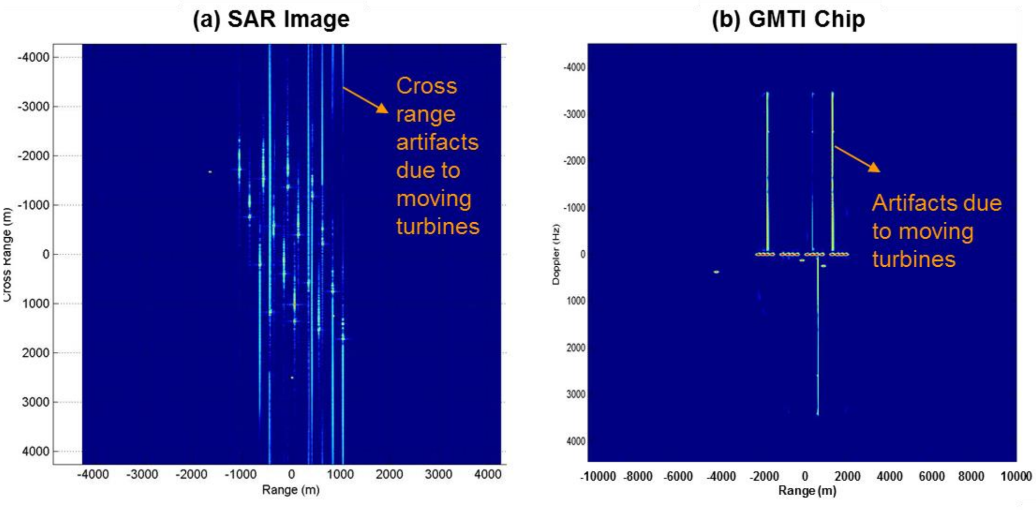


Fig. 5. Simulated SAR and GMTI images from an X-band (10 GHz) airborne radar. The scene contains a 4x4 wind farm with rotating turbine blades as well as three moving boats. (a) SAR image. (b) GMTI chip.

encounter while carrying out surveillance operation around a wind farm. A 4x4 wind farm simulation was used to draw conclusions for this study. The SAR simulations showed that the dynamic signatures from rotating turbine blades cause cross range artifacts in the resulting SAR images (Fig. 5a). These artifacts extend along the cross-range dimension and can be seen beyond the physical location of the wind farm in the SAR image. These artifacts can corrupt the SAR image and the extent of corruption is dependent on sensor parameters. The GMTI simulations showed that the dynamic signatures from rotating turbine blades cause Doppler artifacts in the resulting range-Doppler chips (Fig. 5b). The corruption in the range-Doppler chip is limited to the maximum Doppler extent of the turbine blades, and is bursty in time. These artifacts can potentially interfere with tracking of boats in coastal waters. Some signal filtering algorithms were applied to reduce the dynamic turbine clutter in both SAR images and GMTI displays. They showed good performance in filtering out the turbine clutter when proper filtering parameters were chosen.

Based on this study, we make the following assessments and recommendations:

1) Wind farm scattering could produce serious artifacts in SAR and GMTI signatures generated by airborne sensors when a wind farm falls within the coverage area of the radar beam. This could potentially impact the performance of identification and tracking algorithms.
2) Signal processing of the signatures may be a viable approach to mitigate the effect of dynamic wind turbine clutter. Assuming these mitigation factors are studied and implemented, the impact on recognition and tracking could be reduced to within a moderate level.
3) We did not examine higher order effects such as multiple scattering and interactions with ocean surface. Further study is needed to fully characterize their effects.

HF Radar: A network of HF radar sensors is operated by the National Ocean and Atmospheric Administration (NOAA) for large-area ocean surface current monitoring out to 250km off the US coast. They operate in the 4 to 50 MHz frequency range. Since these sensors must look through any obstructions between the coastline and the ocean by propagating a vertically polarized electromagnetic wave along the ocean surface, offshore wind farm structures may pose a serious concern.

For this case study, we examined the radar backscattering clutter and forward electromagnetic shadow generated by a typical wind farm in the HF frequency range using full-wave computational electromagnetic simulation. Conducting wire-frame models of the turbines were used to speed up the simulation time while capturing most of the scattering physics. Simulation was performed over multiple snapshots to generate the dynamic Doppler information (Fig. 6).

Our findings are as follows:

- Wind farm clutter at HF is sufficiently localized in range. The range extended returns caused by intra- or inter-turbine interactions are weak.
- The Doppler spread of wind farm clutter is limited to the maximum Doppler of the blades, or about ±9Hz at 13MHz. The CODAR system has only a 2Hz sampling rate, so the Doppler spread will be aliased.
- The shadow due to each wind turbine has a shadow depth no greater than 2 dB at HF. The shadow is localized behind each turbine.

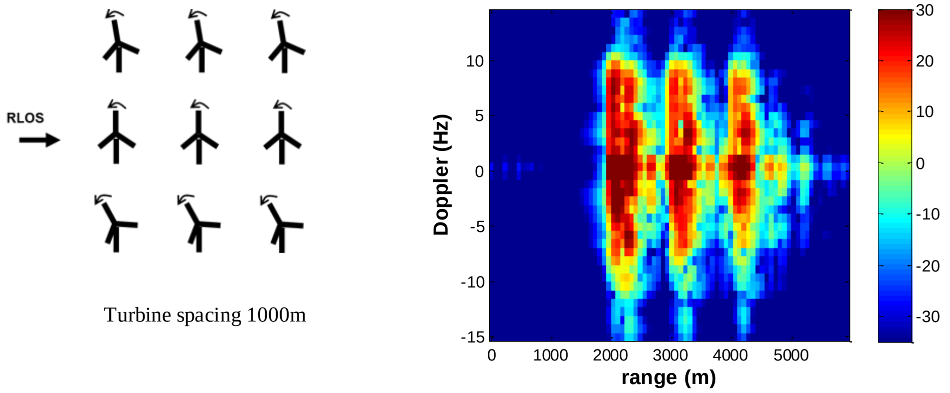


Fig. 6. Range-Doppler plot (in dBsm) of the HF radar clutter from a 3x3 wind farm. The tower height is 90m and the blade length is 63m with a rotation speed of 15 rpm. The radar frequency is swept from 12 to 14MHz, and the radar data is processed over a 120-degree blade rotation window. A monopole excitation at 3000m edge-on incidence is assumed in the presence of an infinite, conducting ground plane.

- There is a moderate increase in shadow depth behind a turbine that is in the shadow of another turbine.
- The overall shadowing effect of a wind farm is not strong and is localized to the region immediately behind the farm from the radar.

Based on this study, we make the following assessments and recommendations:

1) The strength of the wind farm clutter is estimated to be 18dB below the scattered power from the ocean surface being mapped by the radar. However, the turbine clutter may be comparable to the weaker Bragg lines, or second order returns, from the ocean surface that are also of interest.
2) The turbine clutter will be aliased in Doppler due to the slow PRF (2 or 4Hz) that is typically used in these radars, which compounds the problem. Using higher PRF is a possibility, but it increases the data size and may not be compatible with the current system.
3) Our overall assessment is that HF radars may experience interference under certain proximity and operating conditions as the result of typical wind farm configurations.
4) Field measurements are needed to corroborate the modeling results. The next phase of DOE offshore wind projects may provide a good testing ground to collect HF radar data both before and after installation.
5) Mitigation approaches are possible and should be further researched. For example, the combination of range, azimuth and Doppler filtering may be possible to postprocess the data to remove turbine clutter. Mitigation solution needs to be assessed from both the technical as well as cost point of view.
6) The present study is based on perfect conducting turbine components. Dielectric blade materials (possibly with internal structures) should be modeled and studied.

Communications Systems: In addition to their potential impact on radar systems, offshore wind farm structure may also affect communications systems operating in the marine environment. This includes vessel-to-vessel, vessel-to-shore and vessel-to-space links. Examples of systems that potentially may be affected include satellite links such as GPS (global positioning system, 1.6GHz) for navigation and Iridium (1.6GHz) and GOES (400MHz) for data relay by various ocean monitoring sensors, VHF (160MHz) radio for marine communications, and AIS (160MHz, automatic identification system) for vessel tracking.

For this case study, we carried out the modeling of the propagation channel when the transmitter (Tx) or receiver (Rx) is located within or around a wind farm in order to assess the effect of multipath and shadowing on communications systems that are operated within the offshore wind farm environment. An approximate electromagnetic simulation approach was developed to predict the near field distribution around a wind farm from the VHF to microwave range (Fig. 7). It was found that:

- A distinct shadow region is observed behind the tower. Multipath interference is observed outside the shadow region.
- The shadow becomes more optical-like as frequency is increased, leading to longer, narrower and deeper shadows. However, the signal fade is still less than 6dB relative to the direct line-of-sight (LOS) signal up into the GHz range.
- The vessel-to-vessel link can serve as a worst-case estimate of the vessel-to-satellite link.
- The shadow becomes deeper when more than one turbine is lined up with respect to the Tx LOS. However, this situation is rare.

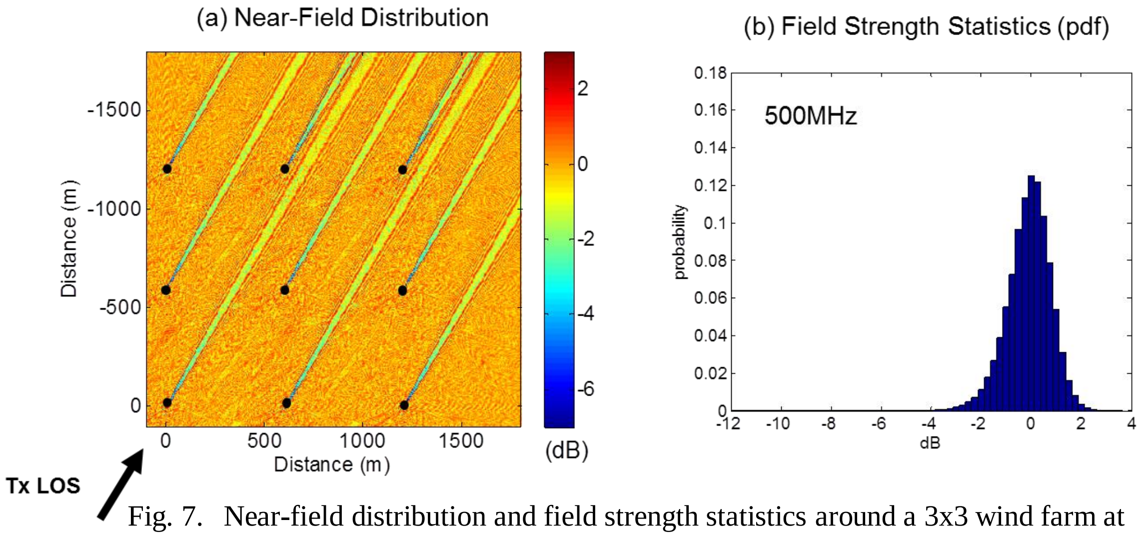


Fig. 7. Near-field distribution and field strength statistics around a 3x3 wind farm at 500MHz. The tower radius is 3.3m and the inter-turbine spacing is 600m.

Our assessments and recommendations are as follows:

1) Most communications systems have built-in link margins to combat signal fading. For example, typical GPS receivers have a fade margin of 15dB or greater.
2) Given the small degree of the signal fade (<6dB) and the finiteness of the electromagnetic shadow found around wind farms, the effect of wind farms on communications systems is expected to be low.
3) When more than one turbine is lined up with respect to the Tx LOS, the fading risk is elevated.
4) The disruption on phase due to wind farms may cause some concerns on those applications where phase information is used, such as direction finding and precise GPS relative and absolute positioning techniques based on carrier phase measurements. These should be further examined.

5) For marine or airborne radar, the shadowing factor computed in this study should be doubled (from 6dB to 12dB) to account for the two-way propagation loss. This may lead to some loss in detection range when either the target or the radar is in the deep shadow of the turbine. However, this is still limited to be a small region behind the tower.
6) Future measurement data collection is recommended to corroborate the results of this simulation study.

3.3. Acoustic Modeling Study.

The most important measure of how underwater noise may impact electronic systems used in connection with sonar, seismic sensors on the sea floor, and other related acoustical applications is the sound pressure level of the noise radiated by the wind turbine towers in relation to the ambient noise in the ocean. Context for the modeling study, and a baseline for the conclusions, should therefore begin with a discussion of the ambient noise.

The principal physical mechanisms by which noise is produced in the ocean are wind-generated waves on the surface, the effect of which increases with wind speed, and shipping noise. Both can change significantly with time of day and season of year. Additionally, acoustical environments in neighboring coastal regions are often very different due to local bathymetry and bottom composition, making it difficult to predict the ambient noise with a high degree of certainty.

Published spectrum levels of ambient noise in shallow coastal waters are scarce at best. One such set of measurements, made along the continental shelf of North America and reported by Piggott (1964), as reproduced with modern notation in the comprehensive compilation Ambient Noise Measurements in the Sea (Urick 1984), is presented in Fig. 8. These frequency spectra, collected off the coast of Nova Scotia over a period of one year in water of depth 50 m, are presented as a function of average wind speed. Piggott reported that “For each hydrophone, the relative spectral-energy distributions of the sea noise were closely the same for all months in a particular wind-speed group. ... Above the limiting background noise, the sea-noise spectrum levels increase linearly with the logarithm of the wind speed over the frequency range 8.4 to 3100 Hz.”

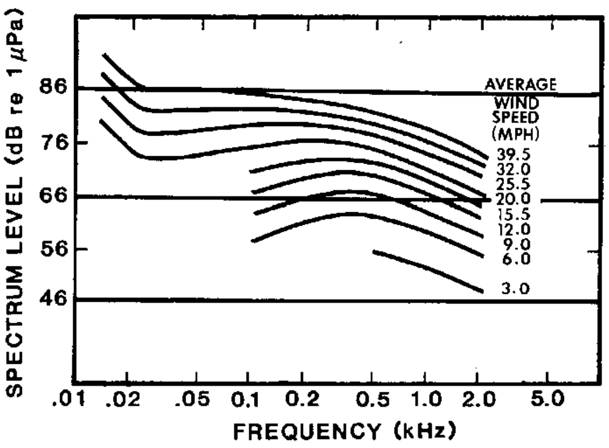


Fig. 8. Noise spectra measured along the continental shelf off the coast of Nova Scotia in water of depth 50 m (Urick 1984, after Piggott 1964). The text in parentheses in the vertical axis label should read “dB re 1 μPa/√Hz”.

From Fig. 3 it is seen that underwater noise radiated by wind turbines is below 1 kHz, in which frequency range the sound pressure levels of the ambient noise spectra in Fig. 8 are nominally between 60 and 80 dB (re 1 μPa/√Hz). Other measurements of ambient sound pressure levels reported for shallow coastal regions in North America and elsewhere around the world are similar to those observed in Fig. 8. For the purposes of the present report, the nominal background noise level in the frequency band encompassing noise radiated underwater by wind turbines in shallow water is thus taken to be a spectral energy density between 60 and 80 dB.

All numerical simulations reported in Appendix C2 are for wind turbines in water 25 m deep, with the supporting towers extending an additional 25 m into the seabed. The towers are modeled as single cylindrical tubes (monopile construction) with 4 m diameter that vibrate radially with a uniform acceleration of 5 mm^2/s, independent of both frequency and position on the tower, in both the water and the sediment. The magnitude of the acceleration was chosen on the basis of comparisons of numerical simulations with reported measurements of tower acceleration and underwater noise radiation at the Utgrunden wind farm off the coast of Sweden that were used to calibrate the source model. In particular, it was chosen to encompass the magnitudes of the strong, harmonically related peaks in the acceleration spectrum associated with the vibrations produced within the gear box at the top of the tower.

The choice was made to model the vibration along the length of the tower as spatially uniform to create a “worst-case” scenario, in the sense of highest sound levels being produced in the water. It represents a worst-case scenario in two ways. The Utgrunden acceleration measurements were made along the portion of the tower above the water. One may anticipate the acceleration to be less in the water and the seabed due to the much higher loads (acoustic impedances) presented by these media in comparison with air. This reduction in “source strength” was ignored. Second, the assumption of uniform vibration ignores the modal structure along the tower that is likely to be established at each of the harmonics. Radiation of sound is most efficient in the case of uniform radial vibration, particularly at low frequencies, because the entire tower pulsates in phase, with the direction of maximum acoustic radiation being radially outward from the tower. No attempt was made to model infrasound radiated by the slow, cantilevered bending motion of the tower induced by unsteady forces exerted by water waves, wind speed, and other sources.

Shown in Fig. 9 are simulations of pressure fields radiated at 143 Hz by (a) a single tower,

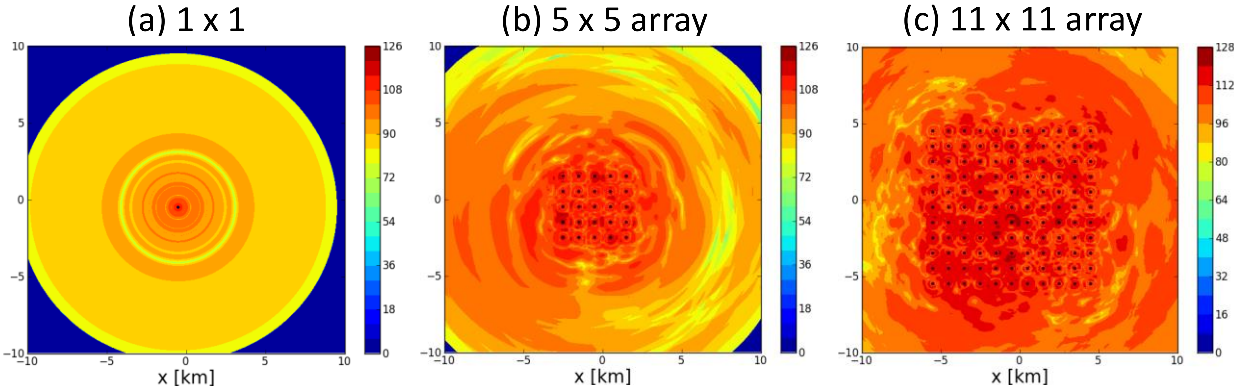


Fig. 9. Pressure field (in dB re 1 μPa, color bars) radiated at 143 Hz for (a) a single tower, (b) a square array of 25 towers, and (c) a square array of 121 towers in 25 m of water over a sandy seabed. The units on the horizontal and vertical axes are kilometers, and the distance between towers is 1 km.

(b) a square array of 25 towers (5x5), and (c) a square array of 121 towers (11x11) embedded in a flat sandy bottom of infinite extent. The acoustical properties of the water channel in which the sound propagates are thus range independent. The frequency is representative of the fundamental of the harmonically related tones radiated by a typical wind turbine tower. The horizontal and vertical plot axes have units of kilometers, and the adjacent color bars indicate sound pressure levels. The inter-tower spacing in the arrays is 1 km.

The sound pressure level at 10 km is about 75 dB for the single tower, about 90 dB for the 5x5 array, and about 96 dB for the 11x11 array. For the square 11x11 array, which spans 10 km on each side, a measurement point that is 10 km from the center of this array is only 5 km from the nearest side, and to that extent the measurement point is still in the near field of this array. It was assumed when calculating the total sound pressure levels in Fig. 9 that each of the towers radiates at exactly 143 Hz. However, as discussed in Appendix C2, it is highly unlikely that all towers radiate at the same frequency. For a variety of reasons (nonuniform wind speed across the farm, random variations in the gear noise, etc.), the sound will not be as tonal as is shown in Fig. 3 for individual towers. Instead, the sharp peaks in the frequency spectrum will be broadened considerably. Because the same amount of energy is spread over a wider frequency band, the sound pressure levels predicted at 10 km from the center of the wind farms depicted in Fig. 9 should be considerably lower. No measurements were identified in the literature which could be used to quantify this effect.

Three types of seabed were considered in the simulations: silt (very soft, highly absorptive), sand (most ubiquitous along the continental shelf), and basalt (very hard, highly reflective). For all three flat seabeds, bottom losses cause the sound pressure level to decay at a rate greater than 3 dB per doubling of distance, the decay rate for ideal cylindrical spreading. Attenuation of sound due to bottom losses is largest for the silt and smallest for the basalt. Comparisons of bottom losses associated with these three seabed compositions are presented in Appendix C2.

Actual bathymetries from the NOAA ETOPO1 database were used to model noise radiation at three potential mid-Atlantic sites for offshore wind farms. These sites are off the shores of New Jersey (-74.14, 39.29), Maryland (-74.80, 38.35), and Virginia (-75.42, 36.82), where the coordinate pairs indicate (longitude, latitude) in units of degrees. The water depth at each of these locations is very nearly 25 m. Going due southeast from the coordinates for Maryland, for example, the water depth remains relatively constant out to a distance of about 100 km, after which the depth increases to about 2000 m over the next 100 km, where deep ocean conditions prevail (see white dashed line in upper half of Fig. 10).

To model long range propagation along the continental shelf and into deep ocean, the source model used to create Fig. 9 was coupled to a standard Navy code (PE, or parabolic equation, solver) that accounts for both the variation of water depth with range, and variation in sound speed with depth in the water column. A standard “Munk profile” was used to describe the dependence of sound speed on depth in deep water, which due to the local minimum in the sound speed at a depth of approximately 1000 m creates an underwater sound channel at that depth. In the simulations, the same Munk profile was (only for simplicity) extended to the shallow water above the continental shelf, defining a decrease in sound speed with depth of approximately 0.1 m/s per meter. Measurements at the Maryland location (courtesy of ARL:UT) indicate that in

January the sound speed increases with depth at a rate of approximately 0.1 m/s per meter (slight upward refraction), whereas in July it decreases at approximately 0.6 m/s per meter (relatively stronger downward refraction). The Munk profile thus provides a slope in between these winter and summer values.

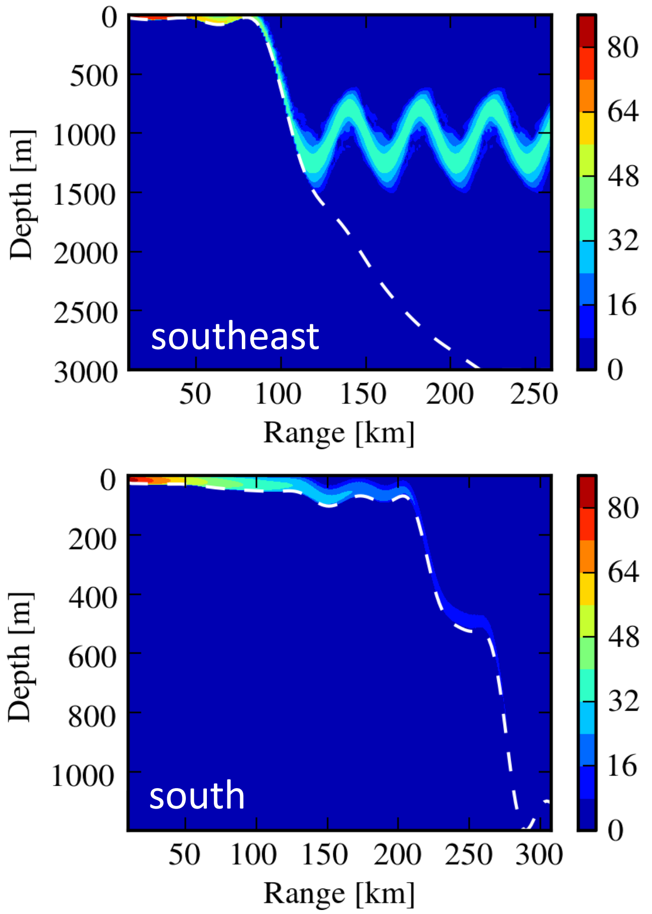


Fig. 10. Pressure fields (dB re 1 μPa, color bars) at 277 Hz propagating due southeast (upper) and due south (lower) from the coordinates of the Maryland site. A sand seabed was assumed.

The simulations presented in Fig. 10 indicate that propagating southeast from a single wind turbine at the Maryland site, the noise at 277 Hz has a sound pressure level of approximately 50 dB as it leaves the continental shelf at a range of 100 m, and it maintains a level of approximately 40 dB after it gets trapped in the sound channel. By comparison, propagating south from the Maryland site the noise is at a level below 30 dB as it leaves the shelf at a range of approximately 200 km.

Simulations were run for radiation at 277 Hz from a single wind turbine for the New Jersey and Virginia sites as well. For the New Jersey site a silt seabed was assumed (arbitrarily, only to show the effect of a soft bottom), and the sound pressure level predicted at the edge of the continental shelf (range of 150 km) and beyond is negligible. For the Virginia site a basalt seabed was assumed (again arbitrarily, this time to show the effect of a hard bottom), and in the eastward direction the sound pressure level predicted at the edge of the shelf (range of 100 km) is approximately 80 dB, after which it is approximately 65 dB in the sound channel. In reality the bottom composition at the Virginia site is expected to be softer (more like sand than basalt), and therefore actual noise levels are expected to be lower. In the southward direction the sound pressure level predicted at the edge of the shelf (range of 200 km) and beyond is negligible.

Our findings and recommendations are as follows:

1) Noise radiated underwater by wind turbines is tonal in nature, characterized by a fundamental frequency between 100 and 200 Hz plus several higher harmonics, with no significant energy above 1000 Hz.
2) Ambient noise in shallow coastal waters used for wind farms nominally exhibits spectral energy densities in the range of 60 to 80 dB (re 1 μPa/√Hz) depending on wind speed.

3) The source model developed for this report, valid for water of approximately constant depth, successfully predicted reported sound pressure levels made in the vicinity of an offshore wind turbine in the Utgrunden farm off the coast of Sweden.
4) Simulations of acoustic radiation from wind farms with up to 121 turbines, in water of constant 25 m depth and three different bottom compositions, reveal that noise levels at long range are very sensitive to bottom composition. More exhaustive parametric studies should be performed to map out this parameter space and provide a database for making predictions at proposed wind farm locations.
5) A simulation performed with real bathymetric conditions at a proposed wind farm location off the coast of Maryland indicates that the noise from a farm with 100 wind turbines will be below the ambient level as it propagates off the continental shelf and into deep water.
6) The model developed for this report was verified by comparison with measurements from only one study (Utgrunden) because it was the only one identified providing measurements of the tower acceleration, which is needed to define the strength of the noise source. Further measurements are needed to verify this and other models under development.
7) Only monopile construction was considered in the source model, which is formally restricted to cylindrical symmetry. However, if provided with adequate knowledge (preferably direct measurement) of the structural vibration, from which equivalent cylindrical source strengths can be estimated, one might reasonably model other constructions that deviate from the monopile symmetry. Potential extensions of the present model to such cases should be examined, e.g., tripod constructions. An entirely different approach may be required to model noise radiation from floating platforms. This too should be examined.

Section 4.
Conclusions and Recommendations

4.1. Conclusions.

In this report, we have described our effort to assess the potential impact of offshore wind farms on sea surface, subsurface and airborne electronic systems operating in the vicinity of offshore wind farms. We have conducted system and literature surveys, sought stakeholder input and carried out first-principle modeling to arrive at our baseline assessment. Our conclusions are summarized below.

First, mitigation processes are in place to deal with existing interference of land-based wind farms on critical land-based radar systems in weather, air traffic control, and long-range surveillance. These processes include mechanisms to evaluate new wind farm proposals, funded research and development programs to examine the various mitigation approaches, and new software tools to better predict the impact. They will be very useful in dealing with the effect of future US offshore wind farms on these same systems.

Second, offshore wind farms do raise some new concerns for other stakeholders. These new concerns include marine navigation and communications, airborne radar, sonar and subsurface acoustical monitoring systems, and coastal HF radars. They will need to be carefully addressed. This report provides a first modeling attempt to examine these concerns. Through our efforts, it was found that:

- Communications systems in the marine environment are unlikely to experience interference as the result of typical wind farm configurations, except under extreme proximity or operating conditions.

- Marine navigation radars and ocean monitoring HF sensors may experience interference under certain proximity and operating conditions as the result of typical wind farm configurations. Pre-deployment investigation is warranted. Mitigation measures may be required.

- Sensitive airborne radars may experience serious interference. However, the degree of interference may be system specific and dependent on whether wind farms are located within the operational area of the radar. Pre-deployment investigation is warranted. Mitigation measures may be required and will need to be further investigated.

- Due to the virtual absence of noise exceeding background levels radiated underwater by wind turbines at frequencies above 1 kHz, interference with underwater acoustical systems is deemed to be unlikely at such frequencies. At frequencies below 1 kHz, the tones radiated by wind turbines may cause interference with certain acoustical systems when placed in close proximity to a wind farm. As noted, “close proximity” can be determined only on a case-by-case basis, as it depends not only on the background noise at the given location, but also on factors specific to the wind farm itself (number of turbines, geometry of the layout, etc.), as well as on environmental conditions (bathymetry, seabed composition, etc.).

Due to the unavailability of system-specific information, we were not able to carry out an assessment at the system-specific level. Instead, our modeling effort focused on electromagnetic and acoustic phenomenology. We believe a more detailed assessment on individual systems may be made by combining the results from our study with detailed system-specific information.

4.2. Recommendations.

The following is a list of recommendations derived from our project findings. They are listed in their order of importance.

First, it is highly recommended that measurement data on electronic systems be collected both before installation and after installation of the new Advanced Technology Demonstration projects funded by the DOE Wind Program. These new facilities, which should become operational between 2015 and 2017, will provide an excellent testing ground to collect in-situ electromagnetic and acoustic data in order to confirm the modeling predictions.

Second, it is recommended that a more complete risk assessment on individual systems be made by combining the results from our study with detailed system-specific information. These are best performed by stakeholders who not only hold such information but have the expertise to make a holistic risk assessment. For underwater acoustics, it is recommended that a future study be conducted that focuses on specific acoustical systems that operate at frequencies below 1 kHz, which was not addressed in the present report. Such a study should include further engagement with stakeholders, including a classified forum in which the Department of Defense may voice its concerns.

Third, it is recommended that research and development into approaches to mitigate the impact of offshore wind farms on electronic systems be initiated through new research funding. The systems to be addressed, in order of their sensitivity to wind farm interference, are: 1) airborne radars operating in high-resolution sensing modes, 2) coastal HF radars, 3) marine radars, and 4) acoustical sensors operating below 1 kHz. For radar systems, particular focus should be placed on low-cost solutions such as those based on signal filtering algorithms or modified navigation practices. In the case of underwater noise, one might investigate possibilities for expanding techniques currently focused on pile driving operations (such as bubble screens, pile sleeves and hydrodynamic sound dampers) to entire wind farm installations.

Fourth, it is recommended that a government working group focusing on the new offshore scenario be established to encourage sharing of information from various agencies and help set protocols for addressing the offshore wind farm interference problem.

Fifth, it is recommended that the development of electromagnetic and acoustic simulation capabilities be continued. Currently, no end-to-end simulation tool exists that can address the various offshore wind farm interference scenarios. An accurate, user-friendly prediction tool will benefit future site-specific assessment tasks. Anomalous propagation effects over the ocean and higher order electromagnetic effects such as those due to multiple scattering, interactions with the ocean surface and non-conducting turbine materials should be further examined.

Sixth, it is recommended that ambient underwater noise measurements be made at potential offshore wind farm sites or, if possible, collected from available databases, and then catalogued for use in future modeling studies aiming to determine acoustical impact.

Seventh, it is recommended that the acoustic source model for underwater noise radiated by submerged wind turbine towers, which was developed under this project, be extended from cylindrically symmetric monopile towers to more complicated but geometrically similar constructions such as tripods, and that a new approach be developed to model noise radiated from floating platforms. Similarly, the implications of new tower constructions should be examined for their above-surface electromagnetic scattering effects.

Section 5.
References

5.1. Electromagnetics

Topic Area 1. Marine Navigation

[EM-1.US1]
"Report of the Effect on Radar Performance of the Proposed Cape Wind Project,"
D. Rugger, A. Pieramico and T. Koontz
Technology Services Corporation (TSC) report to the U.S. Coast Guard
Dec. 2008

[EM-1.US2]
"U.S. Coast Guard Assessment of Potential Impacts to Marine Radar as it Relates to Marine Navigation Safety from the Nantucket Sound Wind Facility as Proposed by Cape Wind, LLC"
Jan. 2009

[EM-1.US3]
"Assessment of Likely Effects on Marine Radar Close to the Proposed Nantucket Sound Offshore Wind Farms"
Captain D. Barber
Marico Marine for Cape Wind Associates LLC
Report No. 08-656
Aug. 2008

[EM-1.US4]
"Revised Navigational Risk Assessment, Cape Wind Project, Nantucket Sound" (Appendix 3.21-A)
ESS Group, Inc.
ESS Project No. E159-501.16
Nov. 2006

[EM-1.EU1]
"Results of the Electromagnetic Investigations and Assessments of Marine Radar, Communications and Positioning Systems Undertaken at the North Hoyle Wind Farm"
QinetiQ and the Maritime and Coastguard Agency
Martin Howard and Colin Brown
QINETIQ/03/00297/1.1
MCA Report MNA 53/10/366
15 November 2004

[EM-1.EU2]
"Offshore Wind Farm Helicopter Search and Rescue Trials Undertaken at the North Hoyle Wind Farm"

Maritime and Coastguard Agency (and RAF)
Colin Brown
MCA Report MSA 10/6/239
May 2005

[EM-1.EU3]
“Report on Horns-Rev VHF Radio and Marine Radar”
Elsam Engineering, DK report to Cap Wind Associates, Doc. No. 186829
Mar. 2004

[EM-1.EU4]
“Investigation of Technical and Operational Effects on Marine Radar Close to Kentish Flats Offshore Wind Farm Kentish Flats”
Marico Marine for BWEA
April 2007

[EM-1.EU5]
“MGN 371 (M+F) Offshore Renewable Energy Installations – Guidance on UK Navigational Practice, Safety and Emergency Response Issues”
Maritime and Coastguard Agency (MCA)
2008

Topic Area 2. Air Traffic Control

[EM-2.US1]
“Impact Study of 130 Offshore Wind Turbines in Nantucket Sound”
FAA, Western Service Area, Engineering Services, Report AJW-W15B
S. Hawk
March 03, 2009

[EM-2.US2]
“The Radar Support System (RSS): A Tool for Siting Radars and Predicting Their Performance,”
B. O’Hern, J. Mack, A. Pieramico, D. Rugger and L. Moyer
1997 IEEE National Radar Conference, Syracuse, NY, pp. 211-216, May 1997.

[EM-2.US3]
“Assessment of the Effects of Wind Turbines on Air Traffic Control Radars”
J. J. Lemmon, J. E. Carroll, F. H. Sanders, D. Turner
NTIA Technical Report TR-08-454 to the U. S. Department of Commerce
July 2008.

[EM-2.EU1]
“The Effects of Wind Turbine Farms on ATC RADARS”
Air Warfare Center, Royal Air Force, UK
May 10, 2005.

[EM-2.EU2]
“Windfarm Characteristics and their Effect on Radar Systems”
C. A. Jackson (BAE Systems)
IET International Conference on Radar Systems
2007

[EM-2.EU3]
“Guidelines on How to Assess the Potential Impact of Wind Turbines on Surveillance Sensors”
EUROCONTROL (European organisation for the safety of air navigation)
9/2010

Topic Area 3. Weather and Ocean Monitoring

[EM-3.US1]
“Impacts of Wind Farms on WSR-88D Operations”
D. W. Burgess, T. Crum, and R. J. Vogt
24th Int. Conf. on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, Amer. Meteor. Soc., Paper 6B.3, New Orleans, LA, 2008.

[EM-3.US2]
“A Way Forward: Wind Farm Weather Radar Coexistence”
J. B. Sandifer, T. Crum, E. Ciardi, and R. Guenther
WINDPOWER 2009, Chicago, IL, May 2009.

[EM-3.US3]
“**New Criteria for Evaluating Wind Turbine Impacts on NEXRAD Weather Radars”**
R.. J. Vogt, T. D. Crum, W. Greenwood, E. J. Ciardi, and R. G. Guenther
NEXRAD Radar Operations Center, Norman, Oklahoma
Windpower 2011

[EM-3.US4]
“Detailed Observations of Wind Turbine Clutter with Scanning Weather Radars”
B. M. Isom, R. D. Palmer, G. S. Secrest, R. D. Rhoton, D. Saxion, T. L. Allmon, J. Reed, T. Crum, and R. Vogt
Journal of Atmospheric and Oceanic Technology, vol. 26, pp. 894-910
May 2009.

[EM-3.US5]
“Signal Analysis and Modeling of Wind Turbine Clutter in Weather”
K. V. Mishra and V. Chandrasekar
IGARSS, pp. 3561-3564
2010

[EM-3.US6]
“Estimation of Wind Turbine Radar Signature at 13.5 MHz”

C. C. Teague and D. E. Barrick
IEEE OCEANS Conference, Hampton Roads, VA
Oct. 2012

[EM-3.EU1]
"Impact of Wind Turbines on Weather Radars"
OPERA II programme, WD_2006_18
Dec. 2006

[EM-3.EU2]
"Doppler Weather Radars and Wind Turbines"
L. Norin and G. Haase
in *Doppler Radar Observations – Weather Radar, Wind Profiler, Ionospheric Radar, and Other Advanced Applications*, J. Bech (Ed.), Croatia: Intech, 2012, pp. 333-354.

[EM-3.EU3]
"**Wind Farm Impacts on HF Radar current and Wave Measurements in Liverpool Bay"**
L. R. Wyatt and A. M. Robinson, and M. J. Howarth
IEEE OCEANS Conference, Santander, Spain
June 2011

[EM-3.EU4]
"Radar, Radio Links, and Wind Turbines"
60th IEA Topical Expert Meeting, Organized by CENER (National Renewable Energy Centre, Madrid, Spain)
Senternovem, Netherlands
Nov. 18-19, 2009

Topic Area 4. Air Defense and Long-Range Surveillance

[EM-4.US1]
"The Effect of Windmills on Military Readiness"
United States Department of Defense Report to the Congressional Defense Committees
2006.

[EM-4.US2]
"Dynamic Radar Cross Section and Radar Doppler Measurements of Commercial General Electric Windmill Power Turbines"
B. M. Kent, K. C. Hill, A. Buterbauch, G. Zelinski, R. Hawley, L. Cravens, T. Van, C. Vogel, and T. Coveyou
IEEE Antennas Propagat. Mag., vol. 50, pp. 211-219
Apr. 2008.

[EM-4.US3]
"Dynamic Radar Cross Section and Radar Doppler Measurements of Commercial General Electric Windmill Power Turbines Part 2 – Predicted and Measured Doppler Signatures"

B. M. Kent, A. Buterbaugh, K. C. Hill, G. Zelinski, R. Hawley, L. Cravens, T. Van, C. Vogel, and T. Coveyou
Proc. 2007 AMTA Symposium, St. Louis, MO
2007.

[EM-4.US4]
“Computational Electromagnetics (CEM) Prediction of a Windmill”
K. C. Hill, G. Zelinski, T. Van, and C. Vogel
2007 Electromagnetics Code Consortium Annual Meeting
May 2007

[EM-4.US5]
“Test Report for Evaluation of Wind Turbines Impact on Long-Range Radar Surveillance at King Mountain, Texas” (For Official Use Only)
Shawn Jordan, 84 RADES (84th Radar Evaluation Squadron), Hill Air Force Base
March 2008

[EM-4.US6]
“Special Technical Assessment of the Cumulative Impact of the Wind Turbines near the Oilton TX ARSR-4 Radar” (For Official Use Only)
84 RADES (84th Radar Evaluation Squadron), Hill Air Force Base
March 2012

[EM-4.US7]
“Wind Turbine Analysis for Cape Cod Air Force Station Early Warning Radar and Beale Air Force Base Upgraded Early Warning Radar”
Missile Defense Agency
Spring 2007

[EM-4.EU1]
“The Effects of Wind Turbine Farms on Air Defence Radars”
AWC/WAD/72/652/TRIALS, Air Warfare Center, Royal Air Force, UK
Jan. 2005

[EM-4.EU2]
“Further Evidence of the Effects of Wind Turbine Farms on AD Radar”
Air Warfare Center, Royal Air Force, UK
Aug. 12, 2005.

Topic Area 5. Communications Systems

[EM-5.US1]
“Electromagnetic Interference to Television Reception Caused by Horizontal Axis Windmills”
D. L. Sengupta and T. B. A. Senior
Proc. IEEE, vol. 67, pp. 1133-1142, Aug. 1979.

[EM-5.US2]
"Electromagnetic Interference from Wind Turbines"
D. L. Sengupta and T. B. A. Senior
in *Wind Turbine Technology*, D. A. Spera, New York: ASME Press, 1994, pp. 447-486.

[EM-5.EU1]
"Co-Sitting Criteria for Wind Turbine Generators and Transmitter Antennas"
C. Salema and C. Fernandes
Proc. Conftelle 1999 – II Conf. de Telecomunicacoes, Sesimbra, Portugal, pp. 466-470, 1999.

[EM-5.EU2]
"TV Interference from Wind Turbines"
C. Salema, C. Fernandes, and L. Fauro
Proc. 3rd Conference on Telecommunications, Figueira da Foz, Portugal, pp. 47-51, 2001.

[EM-5.EU3]
"Report on Horns-Rev VHF Radio and Marine Radar"
Elsam Engineering, DK report to Cap Wind Associates, Doc. No. 186829
Mar. 2004

[EM-5.EU4]
"Results of the Electromagnetic Investigations and Assessments of Marine Radar, Communications and Positioning Systems Undertaken at the North Hoyle Wind Farm"
QinetiQ and the Maritime and Coastguard Agency
Martin Howard and Colin Brown
QINETIQ/03/00297/1.1
MCA Report MNA 53/10/366
15 November 2004

[EM-5.EU5]
"Offshore Wind Farm Helicopter Search and Rescue Trials Undertaken at the North Hoyle Wind Farm"
Maritime and Coastguard Agency (and RAF)
Colin Brown
MCA Report MSA 10/6/239
May 2005

[EM-5.EU6]
"Software Tool for the Analysis of Potential Impact of Wind Farms on Radiocommunication Services"
D. Vega, C. Frenandez, O. Grande, I Angulo, D. Guerra, Y. Wu, P. Angueira, and J. L. Ordiales
Proc. IEEE International Symposium on Broadband Multimedia Systems and Broadcasting, Erlangen, Germany 2011, pp. 1-5.

[EM-5.EU7]
"Empirical Evaluation of the Impact of Wind Turbines on DVB-T Reception Quality"

I. Angulo, D. de la Vega, O. Grande, N. Cau, U. Gil, Y. Wu, D. Guerra, and P. Angueira
IEEE Trans. Broadcasting, vol. 58, no.1, pp.1-9, Mar. 2012

[EM-5.CA1]
"Technical Information and Guidelines on the Assessment of the Potential Impact of Wind Turbines on Radiocommunication, Radar and Seismoacoustic Systems"
Radio Advisory Board of Canada and Canadian Wind Energy Association
April 2007

[EM-5.NZ1]
"Great Valley Wind Farm Compatibility with Radio Services"
Jason Hills
Kordia technical report for Meridian Energy Limited
Dec. 2009

Topic Area 6. Mitigation Techniques

[EM-6.US1]
"Wind Farms and Radar"
Michael Brenner
The MITRE Corporation, Rept. JSR-08-125
January 2008

[EM-6.US2]
"Testimony of Stu S. Webster, Director of Wind Development Permitting and Environmental"
S. S. Webster, Iberdrola Renewables
On Behalf of the American Wind Energy Association to the Readiness Subcommittee of the House Armed Services Committee
June 29, 2010

[EM-6.US3]
"Wind Turbine Impact Mitigation for QVN ARSR-3 Radar"
MIT Lincoln Laboratory report to DOD
June 21, 2010

[EM-6.US4]
"Overview of Raytheon Wind Farm Mitigation Techniques and Test Results"
P. R. Drake
CNS/ATM Conference, Boston, MA
June 2011

[EM-6.US5]
"Radar-Cross-Section Reduction of Wind Turbines (Part 1)"
J. J. McDonald, B. C. Brock, S. E. Allen, P. G. Clem, J. A. Paquette, W. E. Patitz, W. K. Miller, D. A. Calkins, and H. J. Loui

Sandia National Labs, Rept. SAND2012-0480
Mar. 2012

[EM-6.EU1]
“Feasibility of Mitigating the Effects of Windfarms on Primary Radar”
M. M. Butler and D. A. Johnson
Alenia Marconi Systems Limited
2003

[EM-6.EU2]
“Options for Mitigation of the Effects of Windfarms on Radar Systems”
C. A. Jackson and M. M. Butler (BAE Systems)
IET International Conference on Radar Systems
2007

[EM-6.EU3]
“Stealth Technology for Wind Turbines”
J. Pinto, J. C. G. Matthews, and C. Sarno
IET Proc. Radar Sonar Navig., Vol. 4, Iss. 1, pp. 126–133
2010

[EM-6.EU4]
“Stealth Technology for Wind Turbines”
M. Bryanton et al.
BAE Systems, Vestas, U. of Manchester, and U. of Sheffield
Report No. TES 101856
Dec. 2007

[EM-6.EU5]
“Radar In-fill for Greater Wash Area Feasibility Study – Final Report”
D. J. Bannister
QinetiQ Rept. No. ED02698
Aug. 2007

5.2. Underwater Acoustics

Topic Area 1. Noise Measurements

[UA-1.US1]
“Ambient Noise in the Sea”
R. J. Urick
The Catholic University of America
Published by Undersea Warfare Technology Office
Naval Sea Systems Command
Department of the Navy

Washington, D.C.
1984

[UA-1.US2]
“Ocean Noise and Marine Mammals”
Committee on Potential Impacts of Ambient Noise in the Ocean on Marine Mammals
Ocean Studies Board
Division on Earth and Life Studies
National Research Council of the National Academy of Sciences
Washington, D.C.
2003

[UA-1.US3]
“Underwater Acoustic Measurements from Washington State Ferries 2006 Mukilteo Ferry Terminal Test Pile Project”
A. MacGillivray
JASCO Research, 2101 – 4464 Markham Street, Victoria, British Columbia, Canada V8Z 7X8
Prepared for Washington State Ferries & Washington State Department of Transportation
Version 2
March 6, 2007

[UA-1.US4]
“Acoustic Noise and Electromagnetic Study in Support of the Rhode Island Ocean SAMP”
J. H. Miller, G. R. Potty, K. Vigness-Raposa, D. Casagrande, L. A. Miller, J. Nystuen, and P. M. Scheifele
Ocean Special Area Management Plan (SAMP) Volume 2
April 26, 2013

[UA-1.EU1]
“Utgrunden offshore wind farm—measurements of underwater noise”
Ingemansson Technology AB, Göteborg, Sweden
Report 11-00329-03012700
June 17, 2003

[UA-1.EU2]
“Measurement of underwater noise emitted by an offshore wind turbine at Horns Rev”
K. Betke
Institut für technische und angewandte Physik GmbH
Oldenburg, Germany
February 13, 2006

[UA-1.EU3]
“Underwater noise from three types of offshore wind turbines: Estimation of impact zones for harbor porpoises and harbor seals”
J. Tougaard, O. D. Henriksen, and L. A. Miller
J. Acoust. Soc. Am. vol. 125, 3766-3773

June 2009

Topic Area 2. Impact on Marine Mammals

[UA-2.US1]
“Ocean Noise and Marine Mammals”
Committee on Potential Impacts of Ambient Noise in the Ocean on Marine Mammals
Ocean Studies Board
Division on Earth and Life Studies
National Research Council of the National Academy of Sciences
Washington, D.C.
2003

[UA-2.US2]
“Report to Congress on the Potential Environmental Effects of Marine and Hydrokinetic Energy Technologies”
Department of Energy, Wind and Hydropower Technologies Program
Dec. 2009

[UA-2.EU1]
“Assessment of sub-sea acoustic noise and vibration from offshore wind turbines and its impact on marine wildlife; initial measurements of underwater noise during construction of offshore windfarms, and comparison with background noise”
J. R. Nedwell, J. Langworthy, D. Howell
COWRIE (Collaborative Offshore Wind Research Into the Environment, UK)
Report No. 544 R 0424
2003

[UA-2.EU2]
“Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs”
P. T. Madsen, M. Wahlberg, J. Tougaard, K. Lucke, P. Tyack
Mar. Ecol. Prog. Ser., Vol. 309: 279–295
2006

[UA-2.EU3]
“Effects of offshore wind farm noise on marine mammals and fish”
F. Thomsen, K. Lüdemann, R. Kafemann, and W. Piper
biola (biologisch-landschaftsökologische arbeitsgemeinschaft) and
IfAF – Institut für angewandte Fischbiologie GmbH
on behalf of COWRIE Ltd, Newbury, UK
July 6, 2006

[UA-2.EU4]
“Offshore Wind Farms and Marine Mammals: Impacts & Methodologies for Assessing Impacts”

Proceedings of the ASCOBANS/ECS Workshop (10 papers in this compilation)
Editor: Peter G. H. Evans
ECS Special Publication Series No. 49
February 2008

[UA-2.EU5]
"Underwater noise from three types of offshore wind turbines: Estimation of impact zones for harbor porpoises and harbor seals"
J. Tougaard, O. D. Henriksen, and L. A. Miller
J. Acoust. Soc. Am. 125, 3766-3773
June 2009

Topic Area 3. Impact on Fish/Fisheries

[UA-3.US1]
"The effect of anthropogenic sources of sound on fishes"
A. N. Popper and M. C. Hastings
J. Fish Biol. vol. 75, 455-489.
2009

[UA-3.EU1]
"Possible effects of the offshore windfarm at Vindeby on the outcome of fishing: The possible effects of electromagnetic fields and noise"
K. Engell-Sørensen
Tech. Rep. 1920-03-001
Report prepared for SEAS-NVE, Hovedgaden 36, DK-4520, Svinninge, Denmark
January 21, 2002

[UA-3.EU2]
"Offshore Wind Farms—Ecological Effects of Noise and Habitat Alteration on Fish"
M. H. Andersson
Doctoral Dissertation
Department of Zoology
Stockholm University
Sweden
2011

Topic Area 4. Mitigation Techniques

[UA-4.US1]
"Acoustic wave propagation in air-bubble curtains in water—Parts I (History and theory) and II (Field experiment)"
S. N. Domenico
Geophysics 47, 345-375 (1982).

[UA-4.US2]
“Development of an air bubble curtain to reduce underwater noise of percussive piling”
B. Wursig. C. R. Greene, Jr., and T. A. Jefferson
Mar. Env. Res. 49, 79–93 (2000).

[UA-4.US3]
“Mitigating seismic noise with an acoustic blanket the promise and the challenge”
W. S. Ross, P. J. Lee, S. E. Heiney, J. V. Young, E. N. Drake, R. Tengham, and A. Stenzel
Leading Edge March, 303–313 (2005).

[UA-4.US4]
“Underwater Acoustic Measurements from Washington State Ferries 2006 Mukilteo Ferry Terminal Test Pile Project”
A. MacGillivray, E. Ziegler, and J. Laughlin
Technical report prepared by JASCO Research, Ltd (Victoria, British Columbia, Canada) for Washington State Ferries and Washington State Department of Transportation
March 6, 2007 (Version 2)

[UA-4.US5]
“Report to Congress on the Potential Environmental Effects of Marine and Hydrokinetic Energy Technologies”
Department of Energy, Wind and Hydropower Technologies Program
Dec. 2009

[UA-4.US6]
“Mitigation of Underwater Pile Driving Noise During Offshore Construction: Final Report”
A. Stokes, K. Cockrell, J. Wilson, D. Davis, D. Warwick
Applied Physical Sciences Corp., Groton, CT 06340
January 27, 2010

[UA-4.US7]
“**Mitigation of Low-Frequency Underwater Sound Using Large Encapsulated Bubbles and Freely-Rising Bubble Clouds**”
K. M. Lee, K. T. Hinojosa, M. S. Wochner, T. F. Argo IV, and P. S. Wilson
Proceedings of Meetings on Acoustics, Vol. 12, 070006
2012

[UA-4.EU1]
“The use of an air bubble curtain to reduce the received sound levels for harbor porpoises (Phocoena phocoena)”
Klaus Luckea, Paul A. Lepper, Marie-Anne Blanchet, Ursula Siebert
J. Acoust. Soc. Am. 3406, vol. 130
November 2011

[UA-4.EU2]

“Noise Mitigation Measures and Low-Noise Foundation Concepts—State of the Art”

Tobias Verfuß, Projektträger Jülich
BfN-Symposium Towards an Environmentally Sound Offshore Wind Energy Deployment
Stralsund, Germany
January 25, 2012

Appendix A
Details on Survey of Electronic Systems

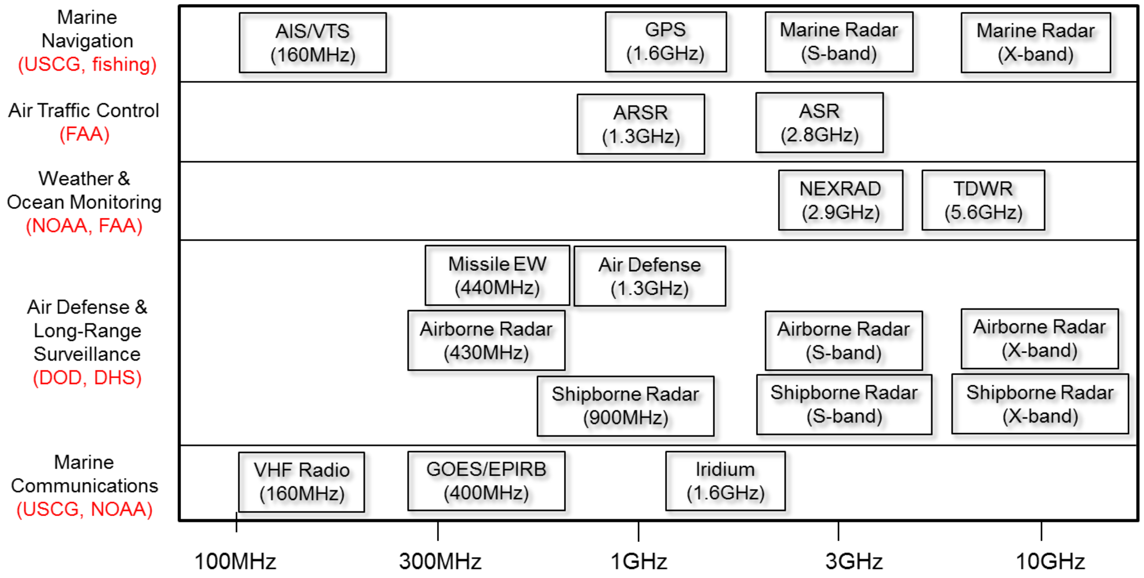
This appendix contains a listing of electronic equipment (marine radar, airborne radar, sonar, navigation and communications equipment) that the project team developed during the initial phase of the project to facilitate stakeholder identification and the subsequent modeling study. The electromagnetics and acoustics teams each developed a systems list versus frequency and applications/stakeholders to help identify those systems that could operate in the vicinity of and be affected by offshore wind farms. Section A1 of this appendix provides such a systems list for electromagnetic system. Section A2 provides the systems list for acoustics systems.

A1. SURVEY OF ELECTROMAGNETIC SYSTEMS

To assist in identifying electromagnetic systems and stakeholders regarding the potential interference from offshore wind farms, a systematic survey was conducted. Systems from 100 kHz to 10 GHz were initially identified, and are shown in an overview chart in Figure A1 versus frequency band of operation and stakeholders. A more detailed listing of the systems and their key attributes are shown in Table A1.

Fig. A1. An overview of electromagnetic systems versus frequency and stakeholders.

Electromagnetic System Survey – Above 100MHz



Electromagnetic System Survey – Below 100MHz

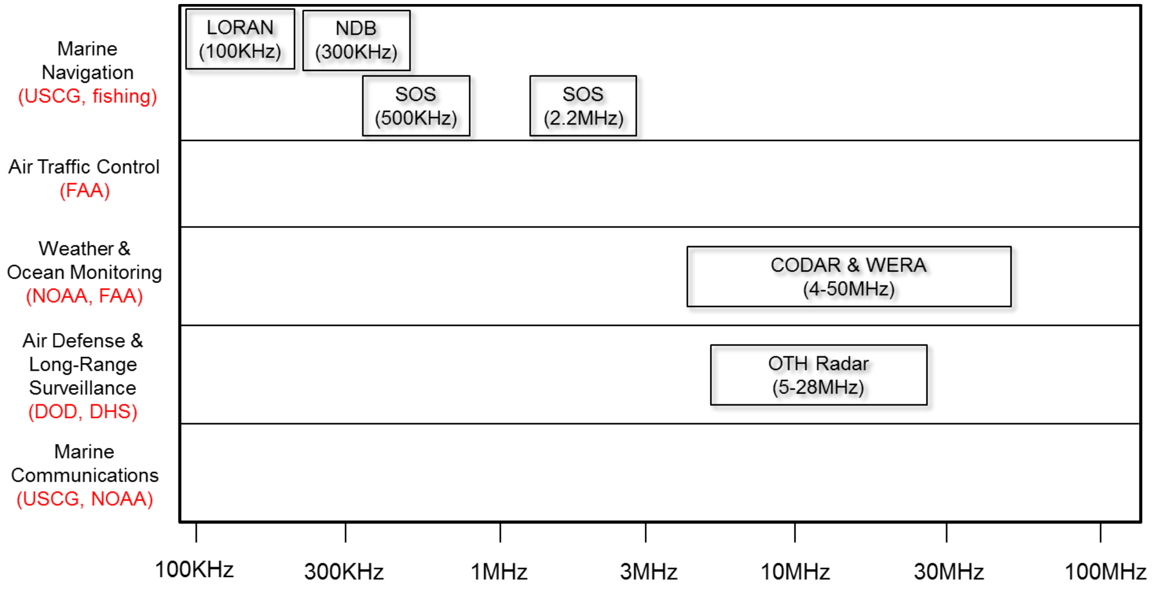


Table A1. Detailed list of electromagnetic systems and their associated attributes.

- Marine Navigation:

System	Description	Attributes
AIS + VTS	Automatic Identification System, vessel traffic service	161-162MHz
Marine radar	collision avoidance and navigation: Small Vessel: Raymarine digital radar Small Vessel: Garmin GMR Small Vessel: Furuno Large Vessel: Kelvin Hughes MantaDigital Radar Large Vessel: Sperry Marine (Northrop Grumman) VisionMaster	 X-band X-band X-band S- and X-band S- and X-band
GPS	Global Positioning System	L1: 1.5754GHz L2: 1.2276GHz
LORAN	in steep decline, being replaced by GPS	90-110 KHz
SOS	International calling and distress frequency (90-280km), similar to channel 16 in VHF (40-90 km). International calling and distress frequency using Morse code	2182 KHz, 500KHz
NDB	Non-Directional Beacon: used in both aviation and marine navigation In North America	190-1750KHz 190-535KHz

- Air Traffic Control:

System	Description	Attributes
ASR-7/8/9/11	Airport Surveillance Radar 9 and 11: aircraft position and weather conditions simultaneously	2.7-2.9GHz
ARSR-4 AN/FPS-130	250 nmiles Joint Surveillance System, for atmosphere defense jointly operated with Air Force	1.215-1.4GHz
ADS-B	Will replace radar as the primary surveillance method for ATC worldwide. Works with GPS.	1090 or 978 MHz

Precision Approach Radar

AN/FPN-63		
AN/MPN-14	15 nautical miles	
AN/MPN-25		X-band
AN/TPN-25	35 km	I-band
AN/TPN-22	tracking while scanning	I band
AN/GPN-22	35km (the only difference between GPN-25 and TPN-22 is the	I- and J-band

	antenna)	
ASR-23SS		L-band
AN/FPN-36	known as QUAD, 40 nautical miles	9-9.16GHz
PAR-80	successor to FPN-36, 20 nautical miles	S-band
AN/TRN-45	15 nautical miles	5.031-5.091 GHz

- Weather and Ocean Monitoring:

System	Description	Attributes
WSR-88D	D stands for Doppler	2.7-3GHz
TDWR	detects wind shear near main airports, funded by FAA	5.6-5.65GHz
CASA	Collaborative Adaptive Sensing of the Atmosphere, NSF-sponsored	X-band
MPAR	Multi-mission Phased-Array Radar, FAA	2.7-2.9GHz

Ocean Monitoring

CODAR	Coastal Ocean Dynamics Applications Radar	4-50MHz
WERA	WavE RAdar	4-50MHz

- Military:

Air Defense

ARSR-4 (a.k.a. AN/FPS-130)	Joint Surveillance System	1.215-1.4GHz
AN/FPS-117	Long Range Solid-State radar, 3D, 250 nautical miles	1.215-1.4GHz
FPS-124	fill-in the gap of FPS-117, 2-70 miles	1.215-1.4GHz
AN/FPS-114	FPS-117 fill-in, cease operation except suspected air-born attack	S-band
AN/TPS-77	transportable version of FPS-117	
AN/TPS-63	Digital MTI, coded pulse, frequency agility, pulse stagger	1-2GHz
AN/FPS-20, 66, 67, 93	general air surveillance, range over 200miles	1.25-1.35GHz

Ballistic Missile Defense/Surveillance

Pave Paw	AN/FPS-115/120/123/126	420-450MHz
SBX	4700km range, sea based	X-band
Cobra Dane	AN/FPS-108	1.215-1.4GHz
Cobra Judy	AN/SPQ-11, shipborne	2.9-3.1GHz

FPS-85	Ballistic	442MHz
UEWR - AN/FPS-132	latest upgrade to EWR	441MHz

Theater Air and Missile Defense

Patriot	AN/MPQ-55, 170km	4-6GHz
THAAD	AN/TPY-2, wideband solid state phase array	X-band
AN/TPS-75	240 nmile 3D radar	2.9-3.1GHz
AN/MPQ-64 SENTINEL	40km, 3D	X-band
AN/TPS-59	similar to FPS-117	1.215-1.4GHz
Aerostat L-88	370km	1.215-1.4GHz

Airborne Systems

E-2	search for ships in sea clutter E-2 operated by **Navy**. Propeller aircraft: FPS-91/96/111/120/125/138/139/145 versions after FPS-125 have **pulse-Doppler** capability E-2D runs APSY-9, which is **AESA**	405-450MHz UHF-band
E-8C, P-8A, P-3, Helicopters	**ISAR** for submarines E-8C: APY-3/7. **SAR** and **MTI** P-8A: APS-137D(V)5 and APY-10. **SAR** P-3 Family: APS-115/116/134/137/150 **(No Big Radome)** APS-115: 8.5-9.6GHz; APS-116: 9.6-10GHz Hellicopter system: APS-124/128/143/147	X-band
E-3	pulse-Doppler, SAR E-3 operated by **US Air Force.** 707 based. APY-1/2, **pulse-Doppler**	S-band
Longbow (Apache helo), APG-78	8km for moving target	35GHz
Predator	AN/ZPY-1: nose-mounted on earlier version: 40km with 0.3m resolution Lynx: as payload in some MQ-9: 30km with 4in resolution	Ku-band
Global Hawk	Integrated Sensor Suite: 3.5 kW peak power MP-RPIP: This is an on-going project.	X-band

Shipborne Systems

AN/SPS-49	2D long range scan, primary air search radar	L-band, 850-942MHz

AN/SPY-1	Aegis, search and track over large area	S-band
AN/SPG-62	radar illumination for final intercept by air defense missiles	X-band
AN/SPN-43	shipboard air traffic control, 50 miles	3.5-3.7GHz
SPQ-9, SPS-64, 67, 73	search/targeting, pulse-Doppler	I-band
MK 23 TAS (Sea Sparrow)	2D target Acquisition System	1.215-1.4GHz

Over-The-Horizon

AN/FPS-118 OTH-B	US Air force. Not in service anymore. **Doppler**	5-28MHz
AN/TPS-71 ROTHR	Us Navy. Texas and Virginia, **Doppler**	5-28MHz

Fire Control

Airborne AWG-9	pulse-Doppler for F-14	X-band
Maritime SPG-60	111km, pulse-Doppler	8-10GHz
Mk15 Phalanx CIWS		Ku-band

- Test, Evaluation, Instrumentation:

AN/FPS-16	Used extensively in missile ranges	C-band
AN/MPS-39	for White Sand Missile Range	5.4-5.9GHz
AN/MPS-36	for several missile ranges, e.g. Vandenberg Air Force Base's western range	5.4-5.9GHz
ALTAIR	Kwajalein Atoll	VHF/UHF
TRADEX	Kwajalein Atoll	L-, S-band
ALCOR	Chirp monopulse	C-band
AN/FPQ-6	NASA Kennedy Space Center - for Apollo program	5.4-5.9GHz

- Marine Communication:

System	Description	Attributes
VHF radio	channel 87/88 are reserved for AIS	156-162MHz
GOES	Geostationary Operational Environmental Satellite for data delay from weather buoys & C-MAN stations operated by NOAA	401.7-402.1MHz
Distress Radio Beacons	EPIRB (Emergency Position-Indicating Radio Beacons) 121.5MHz is obsolete	406MHz
Iridium	Satcom transceiver for DARTS buoys operated by NOAA	1.62-1.63GHz

A2. SURVEY OF MARINE ACOUSTIC SYSTEMS

To assist in identifying marine acoustic systems and stakeholders regarding the potential interference from offshore wind turbines, a systematic survey was conducted. Sensors from 0 Hz to 100 kHz were initially identified, and are listed in the figures in the following figures along with potential stakeholders.

Figure A2. An overview of acoustic systems operating below 1 kHz versus frequency and stakeholders.

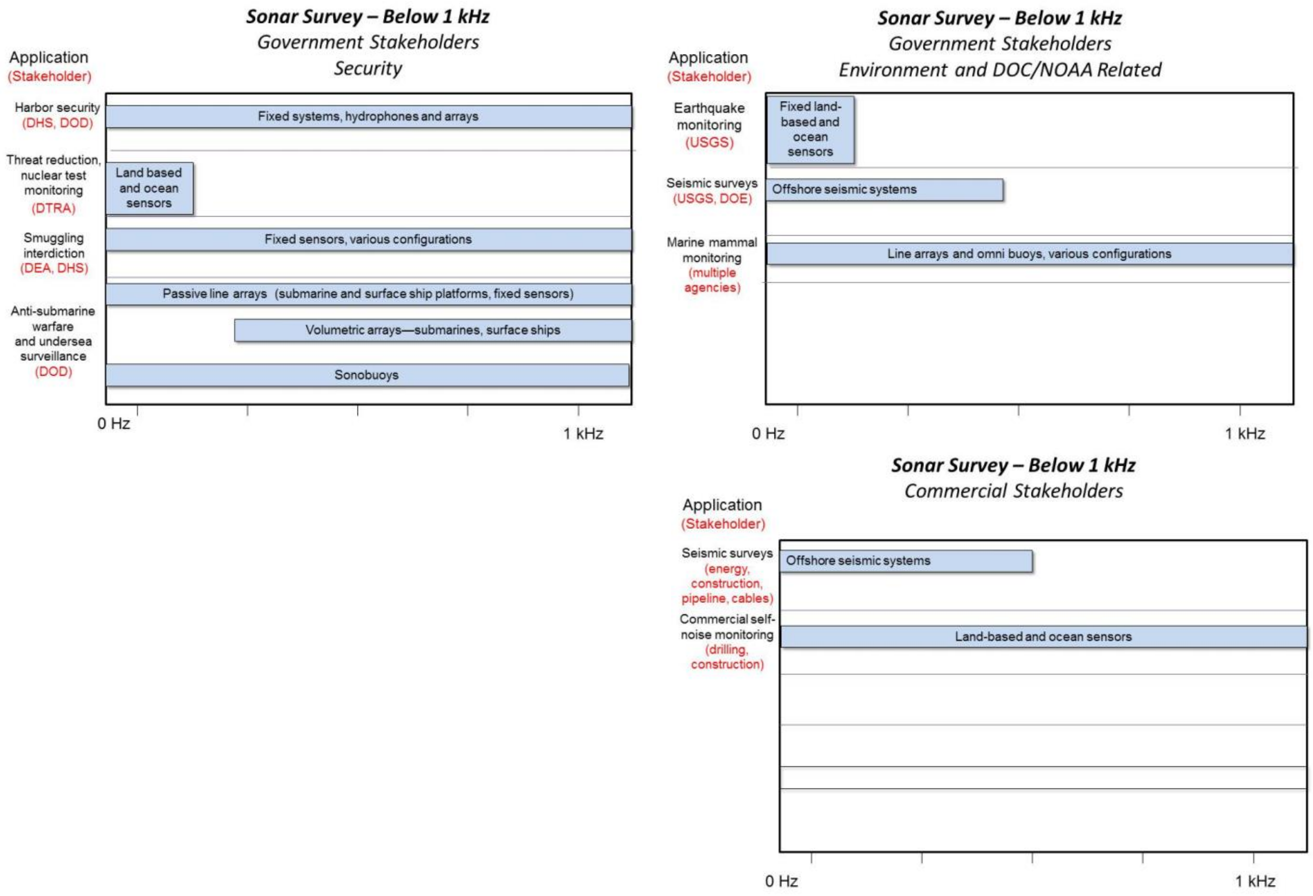


Figure A3. An overview of acoustic systems operating between 1 kHz and 10 kHz versus frequency and stakeholders.

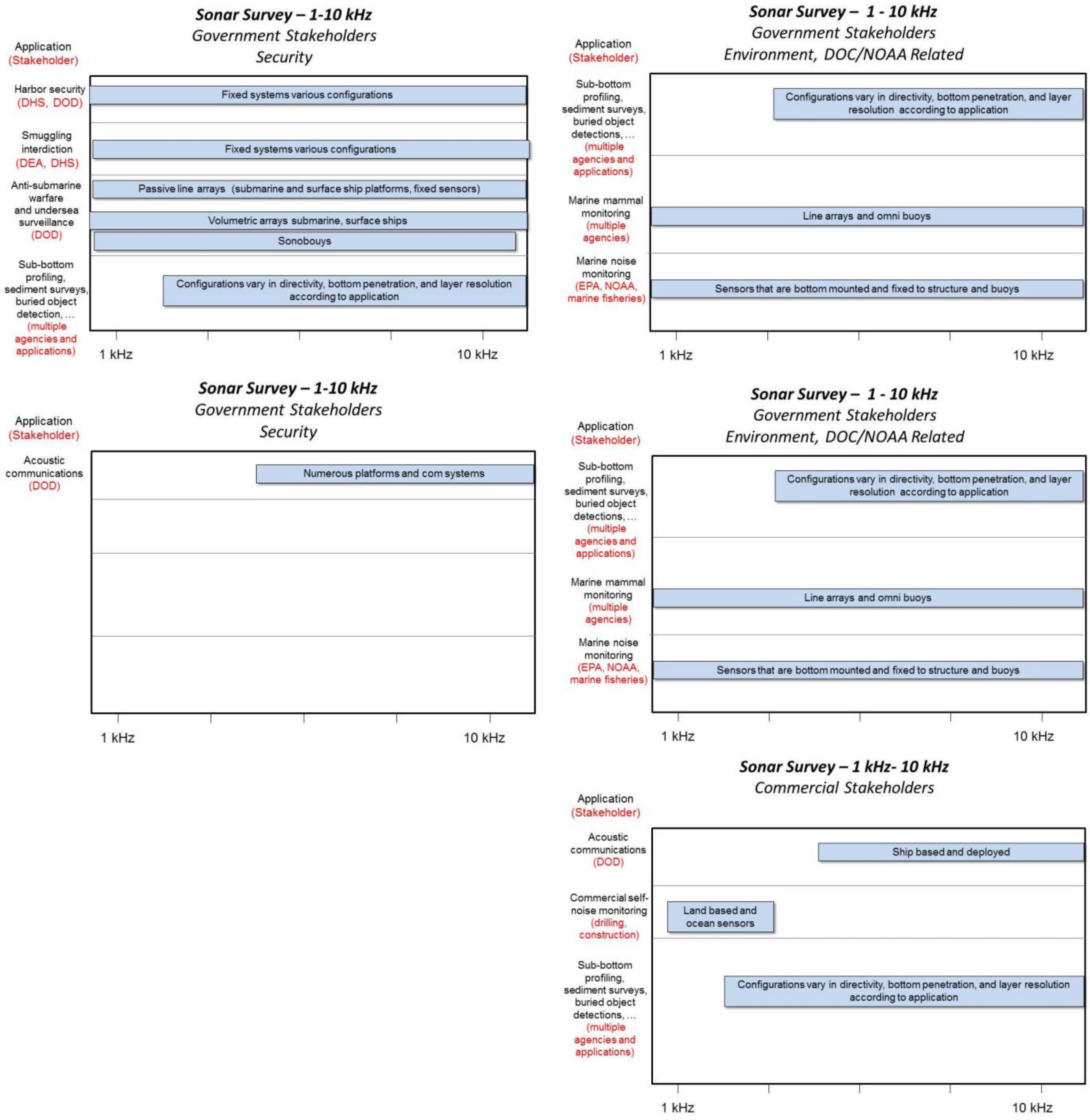
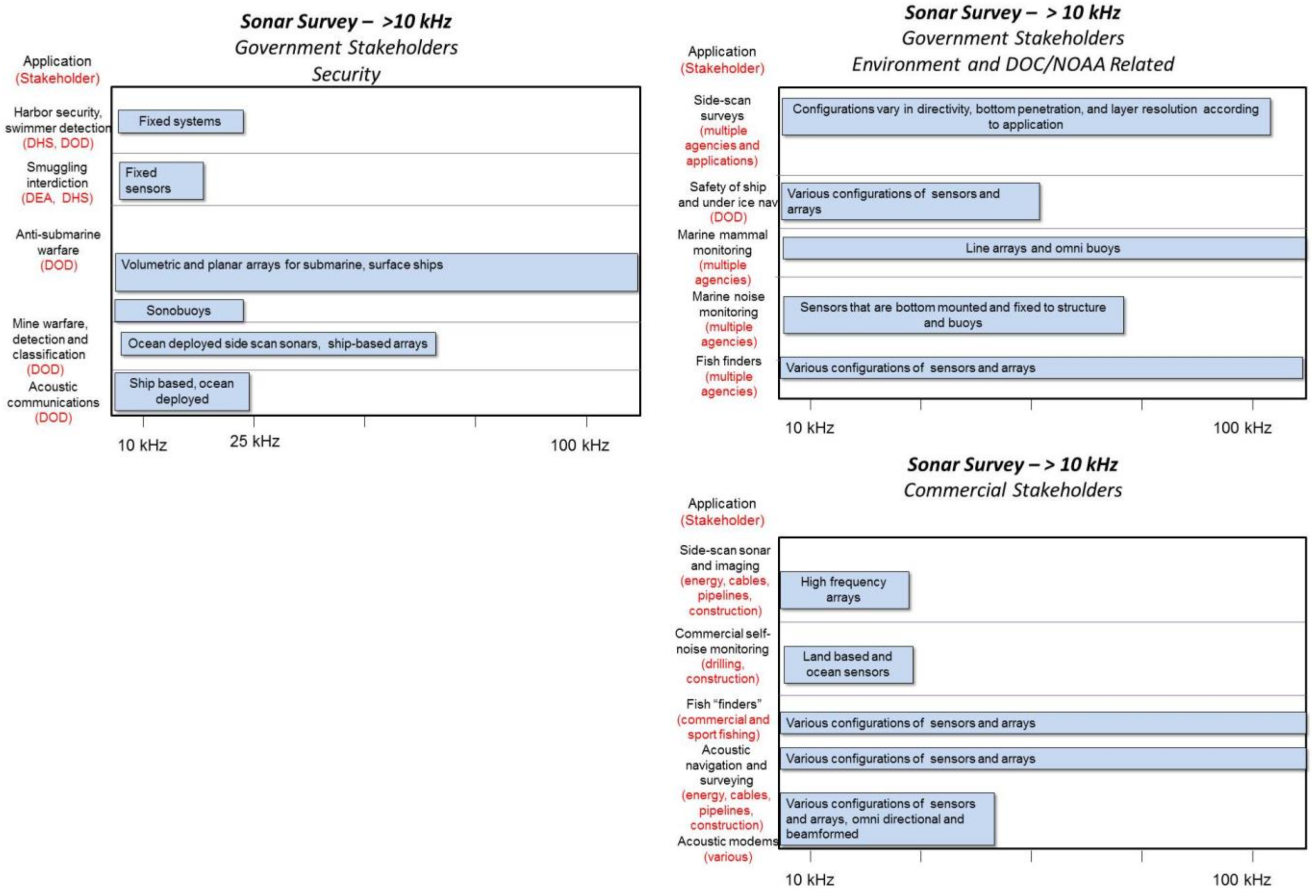


Figure A4. An overview of acoustic systems operating above 10 kHz versus frequency and stakeholders.



Appendix B
Details on Stakeholder Interviews

This appendix describes the details of our effort to engage several key stakeholders to identify the full range of concerns on the effect of offshore wind farms on electronic systems, characterize potential impacts to operations, identify known requirements and options for mitigation, and establish research needs. Personal interviews with stakeholders who agreed to participate were conducted for both electromagnetic and acoustic systems. Through this process, key technical issues were identified and pursued in the subsequent modeling study. Section B1 of this appendix summarizes our stakeholder interview effort in electromagnetic systems. Section B2 summarizes our effort in acoustics systems.

B1. ELECTROMAGNETIC SYSTEMS

B1.1. Methodology

In-depth personal interview was chosen as the appropriate research approach to gather technical information and opinions on the subject matter from a wide range of stakeholders. Interviews were carried out to understand past experiences with land-based wind farm interference and potential concerns with future offshore wind farms on systems operated by the stakeholders.

Initially, a pool of candidates was gathered with the help of DOE and a DOE-hired consultant. These candidates were first contacted via e-mail to request their participation in our study. On average, two follow-up e-mails were sent to encourage participation. The participant pool then expanded via snowball sampling, with the goal to cover as many stakeholder groups as possible. The final list of participants is provided in Sec. B1.2.

Those who agreed to participate were contacted to arrange a phone interview. All interviews were semi-structured, with broad and open-ended questions to allow for a more stakeholder-centric view from the interviewees. The guiding questions used on the interview are included in Sec. B1.3.

The interviews were conducted over two-and-half months during the summer of 2012. The interviews lasted 40 minutes on average, with the shortest lasting 18 minutes and the longest over an hour and half. Some of the interviews were conducted with more than one individual from a stakeholder group during the call. All but one interview were conducted over the phone. The one conducted in a face-to-face format was due to the interviewee being available for an individual meeting. Immediately after each interview, key notes taken were summarized into written form. The interview notes are grouped by agencies and shown in Sec. B1.4.

B1.2. List of Participants[1] (Arranged by Systems of Interest)

George Detweiler (USCG)	LCDR USCG (Ret) Marine Transportation Specialist

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[1] The titles and affiliations of the interviewed participants are those they held at the time the interviews were conducted.

Navigation Standards Division (CG-NAV-3)
Office of Navigation Systems
US COAST GUARD
2100 2nd ST SW, Stop 7580
Washington, DC 20593-7580

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Spectrum Engineering
U.S. Coast Guard CG-652
2100 2nd ST SW
Washington DC 20593-7101

Tim Crum
(NOAA)
Radar Focal Point
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John Yarman (DHS)	84th Radar Evaluation Squadron (RADES) 7976 Aspen Ave Hill AFB, UT 84056-5846
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Frederick C. Engle (DOD)	Energy & Environmental Policy Analyst Office of the Deputy Assistant Secretary of Defense for Readiness 4000 Defense Pentagon, Room 1E537 Washington, D.C. 20301-4000
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Stephen P. O'Malley (Wind Developer)	Director, Site Assessments Fishermen's Energy, LLC. Cape May, NJ

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Kurt A. Olsen (Lockheed TPS-77)	Lockheed Martin Senior Fellow Lockheed Martin MS2 P.O. Box 4840 Syracuse, NY 13221-4840
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Lucy R Wyatt (Offshore wind farm effect on HF radar)	Director Australian Coastal Ocean Radar Network School of Earth and Environmental Sciences Centre for Tropical Water and Aquatic Ecosystem Research James Cook University Townsville, QLD 4811

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Navy Official POC for EM: Nick Ferratella and Wesley Bomyea, OPNAV N43

Navy Official POC for Acoustics: Frank Stone, OPNAV N45

B1.3. Guiding Questions

EM Interview Guiding Questions

This is xxxx from the University of Texas at Austin. My research team and I are conducting a research project for the Department of Energy on the potential impact of offshore wind farms on radar, communications and sonar systems. In particular, we are trying to engage key stakeholders to help us identify all possible concerns about large offshore wind farms. I wonder if I could take a few minutes of your time to get your professional opinions on this issue. This interview will take no more than 30 minutes of your time.

Any identifying information you may provide will remain strictly confidential and separate from the opinions you provide. We ask for such information mainly to help aggregate the feedback for a summary report.

If **NO**, "Is there a more convenient date and time to call you?"

If **NOT THE APPROPRIATE PERSON**, "Is there someone else who'd be more appropriate?"

<If you like, I could send you a cover letter from the DOE describing our effort, and our official statement of project objectives.>

Before we start, for our record keeping, could you tell us your name, the name of your organization, and your current title?
Name:

Organization:

Current title:

(Part I) Do you have any experience with observing wind farm interference on radar or communications systems?

If YES, continue.

If NO, go to (II).

1) Identify the system
   - land based, airborne, shipborne
   - frequency, waveform, signal processing (Doppler/MTI/MTD)
   - maximum range of the system
   - distance between the system and the wind farm

2) Types of interference
   - What happened (specifics of interference, when, where, how often)?
   - How severe was the interference?
   - Did the interference persist over time (different seasons, various weather conditions)?

3) Mitigation measures
   - Were any attempted? What were they?
   - Please describe how they were carried out.
   - Were they effective? How effective?

(Part II) Our study is mainly concerned with future offshore wind farms in the US. Although there is no existing offshore wind farm in the US yet, do you think offshore wind farms could cause interference problems on **your** radar or communications systems?

If YES, continue.

If NO, do you think offshore wind farms could cause interference to **other** radar or communications systems?

If YES, Could you elaborate? [then go to (III).]

If NO, go to (III).

1) Identify the system
   - land based, airborne, shipborne
   - frequency, waveform, signal processing (Doppler/MTI/MTD)
   - maximum range of the system
   - distance between the system and the wind farm

2) Types of interference
   - What kind of interferences are you concerned about?
   - How severe do you think they might be?

3) Potential mitigation measures
   - Do you think there are mitigation measures that can be taken to overcome such interference?
   - What might those be?

4) Any thoughts on other radar or communications systems?

(Part III) Can you think of anyone else we should talk to about this?

Within your organization?

Outside your organization?

Sonar systems?

(Part IV) Before we conclude our interview, is there anything else that you think we should consider?

Thank you for taking the time to share your opinions.

B1.4. Interview Notes

--- DOD#1 ---

(Land based wind farms)

Identify the system
- Most important ones: airport radars (ASR-11), surveillance radar (ARSR-4).

- Test and evaluation systems: Need pristine environments for black world testing. It will be very challenging (e.g. highly classified test facilities out in California or Nevada desert).

- Patuxent River Naval Air Station close to the MD-VA border: may need to keep clear for some sectors of the sky and approach to shore, since they do naval test, air test and some rocket stuff out there.

Types of interference
- Physicists and engineers know what is happening. In a resource-unconstrained world, can design algorithms, new processing models, new displays to make these interference go away. Unfortunately, we are not in a resource-unconstrained environment, and we need to put in Band-Aid solutions.

Mitigation measures
- In-fill radars and changing the radar processor to deal with turbine clutter.

- Raytheon is designing a duplex processor for the ASR-11. Examine the differences between the high-beam and low-beam to track.

- Inside 5 years, confident these problems will be solved (with the exception of when close fly-by or black test ranges).

- Priority list: Airfield: ASR-11, US Northern Command's ARSR-4 and CARSR, NOAA's NEXRAD

- Tyler, MN test happened in April 2012. MIT led the effort. Will process data. Seaspeed 3D X-band in-fill radar (based on a mortar radar) seems to have worked well. Lockheed's TPS-77 (pencil beam radar) seems to be an overkill. It's a resource issue, too costly.

- What is the role of simulation tool? Efforts: NRAD is working on one. BAH, AGI, ATDI are coming up with simulation tools. DHS was working on one, but has pulled the plug on the simulation tool effort by Raytheon. MIT Lincoln Lab is in charge of evaluating these. Getting more faith on these models. Will do flight test on these to verify. Probably 5 years away from having full faith in these tools.

(Offshore wind farms)

- More challenging because of the sub-surface and surface issue, in addition to the air surveillance issues.

- Land based experience can be directly applied.

- Sonar issue could be challenging. Harmonics into seafloor.

- Land based experience can be directly applied. Need to get radar information back to land.

- Have heard of some flight tests against offshore farms off Danish and German coasts.

(Additional comments)

- Am confident we can solve this, other than perhaps a few very specialized test sites.

- US may need a few places for very sophisticated, highly classified tests. May need to preserve some volume of air and ground space for these.

-- **DOD#2** --

(Offshore wind farms)

- The offshore process: BOEM (Bureau of Ocean Energy Management) became the leasing authority for federal waters since late 2009. When a state becomes interested in developing offshore energy, they go to DOI/BOEM to establish a coastal state task force (state gov., tribal gov., federal agencies, but no private industries). The task force conduct assessments on lease blocks for all equities involved (long range radar, fleet operations, training, testing, seabed activities). Assessment has been done on over 2000 lease blocks on the East Coast. Categorized these blocks into: (i) No restrictions (10%), (ii) Site specific stipulations (65%) (developers assume risk), (iii) Wind energy exclusion areas (24%). Goes out 200nmi from an established coastal baseline (to the boundary of exclusive economic zone).

- In the assessment, on radar side, works with NORAD. Wind turbine degrades primary radar. Impact: false targets, clutter. But requires operational assessment.

- Offshore radar evaluation: very rudimentary. Basically based on radar LOS. 1.22*sqrt(height of radar)+1.22*sqrt(height of turbines). When started the process, looked at European offshore farm to come up with a notional farm: 450’ (135m) max. Last year, DOE said eventually will scale things up to be on floating platforms, much farther out. So new forecast based on: 10-15MW, 804’ (240m) height on floating structure. Radar ducting was not considered (ephemeral, short-lived phenomenon). No consideration of water surface vs. land at this initial planning stage. Later on, when the developer submits the COP (construction and operations plan), these detailed questions will be answered then.

- What are some of the radar systems considered? ARSR-4. Some ATC radars (Northcom asked for ATC that reach into Canada, which feed into NORAD). No weather radar. No marine radar (surface search radar) (not a concern for DOD fleet guys) (It highly unlikely any Navy shipdrivers will go into a wind farm. Smaller vessels may go in for training purposes, but right now, not a top concern. Will just avoid the area.)

- Another interesting backdrop: NOAA’s Coastal Service Center is taking a lead role in compiling the Marine Cadastre. National Ocean Policy that came out of Executive Order 13547 (Stewardship of the ocean, our coast and the Great Lakes). Other stakeholders in coastal waters: tribes, commercial fishermen. Moral: many stakeholders already in the coastal waters.

- Acoustics: Have a lot of questions about that. Don’t know much noise will be radiated into the water from either a monopile on the seabed or a floating platform. No one has taken a look at it. UT study will be useful.

-- **DOD#3** --

(Land based wind farms)

- One of NORAD's missions: aerospace control of North America. Surveillance capability requirement: detect small to large airplanes, coordination with FAA, but also have to account for other possibilities (911 type scenarios).

- Radars for US aren't always placed at most advantageous locations. Shared with FAA and DHS. Net result is that we don't have sufficient surveillance capabilities all over the country. So want to preserve current capabilities.

- 2006 NORAD was brought in to review wind turbine projects. To support FAA OE/AAA process. Comes through Long Range Radar JPO (NORAD on the DOD side). Evaluate operational risks for NORAD's air defense mission. 4-5 projects a day. RLOS analysis. Whether turbine projects fall within low-altitude LOS of existing radar systems.

- Radar systems used jointly with FAA and DHS: Long-range ARSR-4; CARSR, legacy ARSR-1/2/3 (to be replaced by CARSR); short-range radars: ASR-7/8/9/11. Long-range AN/FPS-67 series (older).

- PAVE PAW falls within Air Force Space Command.

- Negative impact concerns: (i) generation of false targets (Doppler due to blades), and (ii) desensitization of radar when the clutter occurs in the radar resolution cell. Routinely see false targets with significant density. Desensitization is a lot harder to say since they are insidious.

- Q: Evaluation/projection process vs. actual observation in operational systems, well established in degree of confidence? A: At the learning stage still, but getting better handle. Drawing on various agencies (84th RADES, Nov. 2011 Tyler MN, comprehensive flight trials). DOE-led interagency flight trial on mitigation (Tyler MN, April 2012).

- Analytical tool ROEMS to model resolution cell impact of clutter on detection. Done by AGI (Analytical Graphics). Will be fully delivered by the end of 2011. Now getting a better sense by isolating resolution cell and how it impact detection capability. (DHS tool – looking for a high confidence engineering tool.) NORAD tool is just looking for 80% confidence level. Sufficient for operational stand point.

(Offshore wind farms)

- Through DoD Clearinghouse to evaluate for DOI BOEM lease blocks. Of concern for close-in ones to shoreline. >10-12 miles offshore are less important due to curvature of Earth (unless they grow to very large height).

Q: Can the land-based operational experience and simulation be applied to evaluate offshore impact?

A: Should be fairly straightforward to translate land-based experience/simulation to work. Modeling has baseline clutter model for land. Can be replaced by sea clutter baseline. Main concern: bigger turbines.

Q: Interactions with water? Have not thought about this.

(Additional comments)

- TARS is a DHS system. NORAD does get the information from these sensors.

- Airborne systems have a greater footprint. Degree of impact may be slightly different from land based radars. e.g. AWACS systems…. fighter radars… But have not explored. Relying on the Air Force or Navy to do the research on their own.

-- DHS --

(Land based wind farms)

Identify the system
- After 911, 250 sensors tied together into air defense (full coverage above 5,000' altitude AGL (above ground level)). Tied them into air defense sectors in Rome NY, Seattle, WA, Riverside, CA.

- ARSR-4 (Air Route Surveillance Radar): Long range radar, 3D radar, 250nmile radius reach, along perimeters. 15-20 years old. 44 of these.

- ASR (Air Surveillance Radar): At airports. Also tied into the network.

- CARSR system (Common Air Route Surveillance Radar): Interior US surveillance, 2D radar. Being upgraded. 200nmi.

- TARS: Tethered aerostat systems, southern border, L-88A, 10,000' in the air, tethered to the ground, downward looking, 200 nmi range. 7 systems. (This may be the case where ground bounce effect may be important.)

- Process of windfarm obstruction analysis: JPO receives proposals for various projects from FAA, Army Corp of Engineers, BOEM. Send to John's team at Hill AFB, make technical assessment, tech analysis to DHS (Air Marine Operation Center at Riverside, CA) and DoD (NORAD), then send combined feedback the agencies (FAA, BOEM, etc).

Types of interference
1) Most insidious: Reduction in the probability of detection (PD) in the vicinity of wind farms. Clutter which in turn raises threshold, which in turn reduces PD. Occurs on all of their radar systems, over top of turbines, from ground up to 100,000' (cone of silence).

2) Problems with false targets (Doppler component) that get through target editing.

3) Screening impact from close and tightly spaced wind turbines, usually at close range.

- Lots of work have gone in to study these interferences. Seen in actual operational radar systems, not just test trials.

- Cannot preserve PD. Signal processing was never designed to deal with wind farm clutter (160 knots =80m/s from tip). Goes through MTI, CFAR and target editing. Ends up as false targets. Fills up the clutter map, and raised the detection threshold. Uses a common clutter map, thus reduces detection probability.

- Note that even though ARSR is 3D (9 stack beams in EL), detection losses penetrate through elevation.

- Not as bleak as it looks. Farm may occupy less than 0.1% of the geographical area in coverage. Depends whether the impacted area is near the critical asset area or not.

Mitigation measures
- No silver bullet. Once PD is lost, can't really get it back with anything in the toolbox.

1) Can confine it to the vicinity of the farm.

- Optimization technique to try to limit the impacted area:

- ARSR goes into CP when weather is sensed (loses 3dB in detection). 11.25-deg sector boundary. For wind turbine clutter, use the same 11.25 sector, from 5nmi out to 250nmi. ARSR is V-pol.

- Use "geosensoring" to overlay geo-data to mark (and give up) the area near turbine. Confines the clutter. This gives up PD in the area of the farm, but localizes it to a finer area than the 11.25-deg sector.

This technique has been implemented. Re-optimize the system on a site-by-site basis.

2) When turbines are proposed, DHS archives the proposal, sends it out to 84th RADES for evaluation, report gets generated from that office and goes back to the operational community. Most of the time, they can tolerate it. If not:

- Move wind turbine off their proposed site, or not approve the project at all.

(Offshore wind farms)

Identify the system
Key systems we should consider:
- ARSR-4: Long range radar, pretty close to the coast (perimeter of US), 250 nmi radius reach.

- TARS. Airborne tethered system looking down.

Types of interference
Q: Any other types of phenomenology that would be different from land-based wind farm clutter? A: Expect them to be very similar types of problems to land-based system. (within 60nmi within RLOS, viz., reduced PD over top of farm, false targets, screening effect)

Q: How about propagation over water? Don't know. No in-field tests. Radars are elevated. If radar close to water, maybe multipath issues. Could be predicted by simulation software.

- Gut feeling: some variations, but probably not significant variations from land-based experience.

Q: European study for offshore? A: MoD study. Horns Rev study.

Potential mitigation measures
- 90% sure that land-based mitigation strategies can be transported over to offshore farms.

- Simulation tool: DHS supported Raytheon effort 3 years back to develop a sophisticated tool. $13.5M went into it. Subs: REMCOM/AGI. Complexity of modeling in atmosphere, farm scattering, radar signal processing extremely complex undertaking.

- Use subjective analysis based on in-field experience. Can do a pretty good job.

(Additional comments)

- Two reports (For Official Use Only):

i) 2007 King Mountain, TX tests. In-field study and mitigation.

ii) Oilton, TX Obstruction Evaluation (OE) assessment report.

-- FAA#1 --

(Land based wind farms)

- Manages the obstruction evaluation process (people with air traffic control background). Not radar experts. Reach out to their radar tech ops in the FAA headquarter on radar interference issues.

- Manages based on 14 CFR Part 77 (outlines requirements for notification of construction of objects that will affect navigable airspace, anything >200', <5 miles of an airport). File electronically through on-line site at oeaaa.faa.gov. More details in FAA order 7400.2 Chaps. 5 & 6.

1) Wind turbine cases divided into East and West. A technician is notified and looks at the case file. Verify the latitude/longitude information.

2) Goes into "work status". Notification goes to FAA (airport office, flight procedures office, flight standards office, frequency management office, technical operations office), USAF, Navy, Army (impacts to their airfield and nav aid, DHS (long-range radar). Has 15 days (FAA) 30 days (DOD) to respond. This is when the FAA radar experts in the tech op office get involved.

3) Specialists look at the responses, evaluate them, decide whether to go to the public notice (circularization) (30 days), consolidate and make a determination (notice of hazard or notice of no hazard). If there is an objection, may go into negotiation between the agency and the project sponsor (modify the plan).

- Q: Is the FAA process is in parallel to the NTIA process? Yes, indept. of the NTIA process. The FAA process is regulatory in nature. Not pro-energy.

- Q: How long has the process been in place? Part 77 has been in place since 1965 (oldest record). The automated process started in 2005. Not clear when wind turbine started. In 2007, started to give turbines a special case number 2012-wte-125-oe (wind turbine east) as oppose to 2012-awp-125-oe (western pacific).

- Q: wind turbines more troublesome and handled differently than static structures -> Yes, based on what he's seen from tech ops. Doppler from blades.

- Q: Safe to assume there are no wind farms near airport? Not necessarily. Determination made individually. There may be cases where they are determined to be no hazard. Furthermore, FAA can only make a determination, but no direct authority to tell someone to build or not build. Other siting authority can choose to not issue permit based on the FAA determination.

(Offshore wind farms)

- Q: Any offshore proposal coming through? Not many (Cape Wind, a few in the Great Lakes and East Coast). Cape Wind is the most significant. Ongoing since 2002. Studied it several times. Issued determination in 2006. Determination in 2010. Re-studying again because the court remanded the decision back to FAA.

- Q: Process the same as land based? Same (as far as he knows), except FAA only has statutory authority out to 12 nmi. Not sure if tech ops have any issues with reflectivity of water.

- Q: Concerns with anything that reach into water? Have to look at air traffic beyond radar. Both ASR and ARSR. If radar is affected, can the operation of air traffic control be maintained.

- Tool on the FAA site: wind turbine build-out tool. Put in lat/long. Ahead-of-time pre-planning. DOD preliminary screening tools.

- Q: TDWR run by FAA? Not sure.

(Additional comments)

- Summary: The process is already in place to handle wind turbine obstruction. (No need to develop a new process.) Perhaps a slight augmentation is needed for offshore turbines (on the technical evaluation side, but not in the process itself).

-- FAA#2 --

- Technical operations. Evaluate any obstruction structures (including radio towers, in which case spectrum management is involved).

- Mostly terminal radar (PSR and SSR). Military looks at long range systems.

- Q: TDWR under FAA? Yes. Recent impact due to smoke stack being built. Not aware of any negative impact on the operation of TDWR from turbines. ASR and TDWR reviewed the same way, same engineers.

- Use RSS tool + common thinking. (only for ASR, not TDWR). Looks at false targets. Wind turbine model included. Doppler effect included.

- Use tool developed at Ohio Univ. for VOR (VHF omnidirectional range) and ILS (instrument landing system) for navigation.

- Q: If the regulatory evaluation process is already water-tight, wouldn’t they already stop wind turbine effect be stopped already?   Discussed at the Great Lakes conference.

- Q: Do you see wind farm clutters in existing terminal radars? Absolutely, but seeing clutter doesn’t mean they impact air traffic.

- Q: Localized to the range-AZ cell? Yes, no false targets outside. All elevation? Yes.

- Q: Basically check to see if turbines come into the RLOS? Is there any hard distance limit that you impose to exclude farms from the radar? A: Check the full 60nmi range. Neglected if it is outside the RLOS. Otherwise take a closer look.

- Q: Any special consideration for offshore farms? Not aware of any special consideration. For Cape Wind, that’s what they did.

- Q: What about propagation ducting? Not considered. Purely size. RSS considers water and terrain differently. Cultural database, it would do calculation based on that.

- Q: What percentage of terminal radars is looking into water? Do not have data. 244 ASR in the country. Even if they are near the coast, doesn't mean they are used to track airplanes over water. Once a plane is over water, they are handed over the enroute long-range radar.

- Mitigation: Looks at moving target detection filtering. STC (Sensitivity time control) for suppressing strong nearby ground clutter. Blink out cell (but will not detect target).

- Stuck on cumulative effect: many turbines. Not able to mitigate a large farm successfully at this point.

- Q: easy to retrofit? Long range radar: putting in a SOA processor. Not the intent to mitigate turbines, but hopeful that they can be used to mitigate turbine interference. Terminal radar: ASR-11 is the latest ASR, and is having a new processor being installed. Not proven to mitigate anything yet. Being investigated at this time. DOD has contracted Lincoln to see if they can mitigate their long range radar. FAA does not have any active project to investigate turbine effects. FAA goal is to maintain current systems.

- Q: Mitigation: gap-filler radar? All still on the table.

- Digitize analog radar output (TDX-2000, Sensis Corp).

- ASR-9 and ASR-11 are digital radars. Recent upgrade: 9-pack processor automation card for ASR-9. Desensitization while cancelling out the wind turbines (a compromise).

- Air traffic controller is still part of the loop. Iterative process. Get controller to agree to the test and buy off on the changes.

-- **FAA#3** --

- Works on impact on ATC systems due to wind turbines. Did initial work on modeling of turbines. Develops software tools and guidelines to institute across FAA. Evaluation of turbine cases as they are submitted to FAA. LOS modeling, clutter, weather radar systems, write impact statement for NEXRAD systems.

- Systems: ASR (9, 11), ARSR (3, 4, CARSR (common ARSR, to replace ARSR-1 and -2)), Weather (NEXRAD, TDWR). Not responsible for Navigation, ILS (Instrument Landing System, 110MHz).

- Beacon system: Never there long enough to cause a problem. None. No problem. No false targets. Even at 1 to 2 miles away. Seen them on individual pulses, but not multiple pings to register. Even though they cause problems off static structures (water towers, etc), never for turbines. Positioning accuracy? Maybe. Have not seen it. Not in real data.

- TDWR: Can see the turbines. Not enough empirical data.

- Affected: ASR-9, ASR-11 (expect it to have turbine processing), ASR-8. Farm is particularly bad.

- Analysis tool ensures no turbines are built too close. Uses Lucernhammer. Then radar analysis (RSS, terrain, cultural database), augment with cross sectional software as input. Determine impact. Use worst case analysis. 3dB good enough. Tools are partly validated. Not exhaustive. Empirical data seems to support analysis (loss of detection).

- Shadowing issue: partially due to large clutter cell (limitation due to lack of memory), when you raise the threshold, you lose sensitivity over a large area (quarter mile).

- No good solution. Mitigation: dual-beam processing (European), etc. But has not implemented anything. Things that will work with existing hardware/software. Narrowing of clutter cell. Apply additional STC (sensitivity time control). Radar absorbing materials…

- Q: software solution is sufficient? Old radar does not have the hardware power to handle the software. So many things need to be changed. With the current system, not very optimistic. Old terminal radar, there is no mitigation being planned. Upgraded to new radar, more promising.

- Ocean can affect both terminal and long-range surveillance radar.

- Analysis different from ground based turbines -- 2nd order effects that due to multiple effects off the water surface.

- Cape Wind: Bounce off water may be strong, but beyond our problem capability.

- Propagation issue: Ducting effects. Search radar return over water: ducting is important for clutter artifacts. May enhance clutter. Hard to predict. Not in RSS. RSS has simple multipath tool (can be used for water surface). Does not use EREPS.

Summary:

Analysis tool: “Already have reasonable tools to determine and prevent effects.”

Mitigation: Still a big problem. Daunting task to retrofit on older systems. New radar processing needed.

-- **FAA#4** --

(Land based wind farms)

Identify the system
- Terminal Doppler Weather Radar (TDWR)

- 5.6 to 5.65 GHz.

- 45 are operational (fewer in the west), 2 are for testing in OKC.

- Radar has a long range (up to 460km), but within 50 nmi (or 90km) are important (runway-specific weather products).

- range resolution 150m, angular resolution 0.5 deg (0.55deg beamwidth).

- Compared to NEXRAD, finer resolution, but cannot see through rain or hail.

- One scan every minute (at 0.1 to 0.3 deg EL)

- unambiguous velocity is 10-15 m/s (below turbine Doppler of 80 m/s)

Types of interference

- Nothing has been observed so far. There have been proposals to put wind farms close to TDWR facility. May see interference in due time, but has not happened yet.

- Reason for not seeing interference: TDWR is a "terminal" radar. Interested in range within 50 nmi of an airport. Putting up wind farms near airport has been avoided up to now, since wind farm effects on ATC is an important aircraft obstruction issue.

- Relationship to ATC radar: TDWR are located off airports (within 20km), looking for microbursts above the airport, whereas ATCs are on airport properties. (ASRs has a 60nmi range)

- TDWR has similar processing (and therefore effect) to NEXRAD, since they are both weather radars. However, wind farm interference is less prevalent than NEXRAD due to their locations.

- Possible effects: reflections from tower, blades. Create effects on reflected power, Doppler velocity and clutter filtering.

(Offshore wind farms)

Types of interference
- Some TDWR are on the East Coast going a little into the water (Florida, Northeast, San Juan, Puerto Rico). Perhaps a half dozen of these will breach into water.

Potential mitigation measures
- Outside of terminal area (50 nmi) at minimum, so no contamination on runway-specific weather products.

- Depends on the number of turbines. Not sure if they'll be able to mitigate the interference. Have not seen anything that will work.

- Have been in discussion with NEXRAD, who keeps a good database on land-based farms. Some developments may come close to terminal areas.

- FAA obstruction certification process. e.g. the Marine Corp wants to put up a wind farm near the NYC TDWR. Had to put up a turbine that's much lower than the TDWR beam.

- FAA Regional office will make a determination of whether it's acceptable. TDWR office will make an engineering analysis. No particular tools - RCS, impact on clutter, potential impact on weather product, radar range equation, radar clutter rejection, etc.

-- NTIA --

- The only formal process he knows of is through the FAA obstruction evaluation process, which is based on height only.

- NTIA is a "mailbox" for wind farm applicants and funnels the proposals to the 19 agencies in the IRAC (Interdepartment Radio Advisory Committee).

- Agencies express concerns after a quick/broad analysis.

- Feedback is passed back to the applicants. NTIA is not involved after that.

- Typical comments: Biggest issue is radar. Rarely, if ever, get communications blockage issues. DoD has a clearinghouse already, and rarely participates in this process. FAA has a clearinghouse already. So NOAA is the main participant usually.

- People he talked to told him NTIA is now seeing about 75% to 90% of the wind proposals. However, he's not certain.

- NTIA has no authority over the agencies or the wind developers, trying to fill a void in the short run, hoping there would someone to take over the coordination process, but no one has picked this job up. Has been ongoing for about more than 5 years already.

- Not sure if there are any offshore wind proposals coming through.

- EMI issue: No one in the US has authority over EMI from wind turbines.

--- **USCG#1** --

- CG went to DOE first with topics (sent us the document he originally submitted to DOE)

- Concern started with Cape Wind. (UK Marico study vs. Eli Brookner) Contracted to TSC for a 3rd unbiased look.

- Asked DOE to get a project going to take a look. Whether wind farm would interfere with the entire bridge suite. Mitigatable? (through radar software adjustment, change in placement, operator training)

Key points:

- Interested in shipboard radar and "black boxes on the bridge" (bridge suite including all electronic systems, AIS, communications equipment, radio, etc).

- TSC study is sufficient for decision making in Cape Wind. Just need more scenarios. More systems (Navy, commercial). More exhaustive.

- But want a definitive answer, information provided should be succinct. "Worse than we thought" "Nowhere near as bad as people made it out to be"

- Simulation capability would be very useful. (This would let people do their own study in future situations. It would also provide a way to train operators to discern wind farm effects.

- Another aspect needed for the CG is to create "routing measures" for vessels to get around wind farms. How much should the buffer zone be? Currently use MGN-371 (UK Maritime Guidance Note, available on the internet). Medium or high risk if < 2nmi from farm. Would like to get a better answer on this type of guidelines.

- Concerns from fishermen's group. However, they are not interested in/familiar with electronic equipment. The CG will be the one who will ultimately need to decide on navigation safety.

- UK studies on marine radars: QinetiQ on North Hoyle (2004). Marico study=Kentish Flats (2007). (Both already in our database)

--- **USCG#2** --

- Looks at RF issues for the Coast Guard.

- Cases come to him through the NTIA process. Energy companies or local government. Responses usually come from CG, NOAA, Navy (or Air Force, he can't recall), DOJ. Given 6 weeks to respond. Many proposals come through (1-2 per month). Has only seen one offshore proposal. Looks at where they are located (Pacific, Atlantic, Great Lakes, Gulf of Mexico). Use a government-wide database, plug in coordinates, see if there are any radio transmitters in the vicinity (50-100km).

- Uses Spectrum 21 (put out by NTIA) software (provides coverage maps, based on the NTIA web site). Looks for Tx operated by the government. The database contains all government assignments (>50,000 of them).

- Potential impact in only one instance in the San Francisco area. Blades protruded into the Fresnel zone in a microwave (5GHz) data link. Used a contractor (ATDI) to assess impact. But ATDI said it's ok after using software HTZ Warfare (radio planning tool) to evaluate. He gave thumbs-up as a result of the evaluation.

- Systems: Mainly concerned about systems above 400MHz up to 9GHz. e.g. RF beacons on buoys. Radars. HF communications less important.

- Most of the assessment he has done are for land-based farms.

- Any observed interference cases for CG: Not to his knowledge.

- Mitigation measures: No mitigation plan in place.

- He is also working with people building new Coast Guard cutters. Different systems: radar, VHF radio safety systems. Goes to NTIA for meeting specifications to get a license and frequency assignment to operate them. One license, multiple systems.

- Conclusion: main problem is on radar, not communications.

--- **NOAA#1** ---

(Land based wind farms)

Identify the system
- NEXRAD (WSR-88D) system

- Doppler processing -> can take out stationary clutter

Types of interference
- Can see rotating blades at a fairly long distance (100 miles out).

- Fairly persistent, especially when wind turbines are close in.

- Severity divided according to distance: <3km (very severe), up to 18km (significant), >18km (workaround possible).

- Phenomenology for <3km: beam blockage (similar to what's observed in blockage by towers), partial shadowing possible

- Phenomenology for <18km: multipath effects due to terrain, ghosting (range-extended return up to 3x range and Doppler smearing)

Mitigation measures
- Train forecaster to distinguish turbine clutter from storms (but data product still contaminated)

- Use multiple elevation scans to distinguish contaminated EL angles (limited effectiveness at close-in range since WT clutter penetrates multiple EL scans)

- Filtering algorithm (some research, but not mature yet. Need real-time processing capability)

- Curtail wind farm operation during severe weather so that they do not give rise to Doppler clutter (requires cooperation from and coordination with wind farm operators)

(Offshore wind farms)

Identify the system
- Only 4 or 5 out of the 160 NEXRAD radars are potentially affected by offshore wind farms.

- The above numbers were subsequently updated to 15 out of 159 systems (9 on East Coast, 3 in the Gulf, 3 in the Great Lakes).

Types of interference
- No experience.

- Potential issue: the 18km safe zone distance was arrived at using a 160m-tall turbine. If offshore system is even larger, this may require a new estimate.

- Potential issue: sea clutter and its interaction with offshore wind turbines may give rise to additional phenomenology. Simply do not know at this point.

Potential mitigation measures
Making sure new offshore wind farms are kept at sufficient distance from NEXRAD radars. NWS does not have authority over wind farm development, so they would really like to be in the loop to make sure that new developments do not interfere with their operation.

Any thoughts on other radar or communications systems?
- TDWS (Terminal Doppler Weather Radar) data are included in NWS data product.

--- **NOAA#2** ---

(Land based wind farms)

Identify the system
- HF Radar (130, every coastal state plus Porto Rico, except Texas) (close to 60 in California, 30 in mid-Atlantic). 4 to 50MHz. Operate 24-7.

- Vast majority of them are CODAR systems, only 13 non-CODAR (4 phased arrays developed by U. of Hawaii, 9 WERA systems). Same range resolution.

- Doppler processing.

- 3 CODARs to be turned on in July in Alaska.

- Waveform is FMI(interrupt)CW for CODAR and FMCW for WERA.

- Operates in the monostatic mode. However, CODARs have had multi-static capabilities for over 10 years. It is however not used currently in the HF network.

Types of interference
- Land-based wind clutter has not been an issue, perhaps due to (i) less favorable propagation over land vs. ocean surface, (ii) current radar sites may not be near current land based wind farms. Have done study for NTIA, but have not been raised as an issue.

- Does interfere with HAM radio operation in the immediate vicinity in this frequency band.

- At the very low frequency (5MHz) end, does couple into skywaves and there is interference concerns within the international regulatory agency (WRC).

Mitigation measures
- May be able to put CODAR on floating platform, or even on wind turbines, as an instrumentation platform. This may be a way to avoid the blockage created by wind farms.

(Offshore wind farms)

Identify the system
- An in-house study was done by CODAR Ocean Sensors (experienced engineer and inventor of CODAR). Not commissioned by the government. Used NEC simulation to study potential interference. Will try to get permission from CODAR to release the report to us.

Types of interference
- Doppler clutter from wind farms can compete with ocean wave returns.

- Asked about shadowing issue. Jack’s first reaction is that he does not think so.

Potential mitigation measures
- One method is to increase the PRF to give a bigger Doppler window, so that wind farm clutters are not aliased as badly in the Doppler spectrum to contaminate the ocean returns (current sampling rate is 1 to 2Hz, while a 80m/s wind turbine tip Doppler is 160Hz at 30MHz).

- Down sides are: (i) Data files are bigger. (ii) May not be compatible with the currently system of using GPS synchronized timing to eliminate interference between multiple CODAR systems. May not be able to accommodate as many systems. Need to look more carefully at this.

- Another method is to design software filter to take out the wind farm clutter. (However, this would be hard if the WT clutter is badly aliased.)

- Downsides are: (i) Implementing them will be a new added cost. (ii) NOAA is chartered to provide real time data, and real-time processing at each CODAR site will be required. (Currently, data are I/Q processed down to radial velocity at each site.) The processing may need to site specific.

- These impacts could be mitigated. However, the two methods for mitigation are not desirable as there will be costs associated with them. Lastly, there may be opportunity to assess these impacts in a real-world situation when the first turbine goes up but the mitigation methods would need to be rapidly assessed and implemented so as to minimize the contamination of data.

--- NOAA#3 ---

(Offshore wind farms)

Identify the system
3 types:

- Meteorological and oceanographic buoys (or weather buoys on water), and coastal marine automated network (C-MAN) stations (on shore). Measure wind speed, wind direction, barometric pressure, current profiles, conductivity, surface temperature, depth.

- DART (tsunami detection) buoys: water column height measured by pressure sensors at the bottom of ocean. Satellite link to shore. Goes into high-res mode when a tsunami is sensed. Located around Pacific Rim. Fewer in Altantic/Gulf.

- Tropical Atmosphere Ocean (TAO) Array: measure ocean temperature profile for El Nino prediction. Located near equator. Square grid of array spanning 700m.

Types of interference
1) Concerns about EM energy put out by these wind farms. ("rotary generators spills out RF emission")

- Interference with communications data relay.

- Provided frequency and power output by these transmitters in a table (attached file).

- GOES transceiver. Transmits with high power (89W EIRP). Does not receive downlink from GOES satellite.

- GPS receivers. Could be a concern because of the low signal levels of the received signal.

- Iridium transceivers on DARTs. Rx signal power level is about -138 dBW. But DARTs are a few hundred nmi from shore.

2) Multipath fading and shadowing when too close. Have observed such effect on transmitted signals due to ship passing by in-situ and due to metal buildings in their test facility (a few hundred meters away). Affects uplink to the GOES satellite (401MHz). Have not seen much multipath on Iridium (1.6GHz) but there is no EIRP records of signals reaching the Iridium satellite, like the GOES). "However, beyond say 1000m, this will be less of an issue." Buoys are picket line fenced at 25 nmi offshore… Therefore, multipath interference from wind farm structure should be very minor.

On the other hand, C-MAN stations are on-shore, thus closer to the wind farms. However, they use directional antennas and have higher transmit power. Effect on GOES is probably less susceptible to multipath.

- DART uses Iridium transceivers, omni antennas, very far offshore (few hundred nmi). Not really a concern.

"Don't see a lot of impacts" for this multipath (DARTS-very far, weather buoys-far, C-MANS are closer, but they use directional antennas, so not very susceptible to multipath interference).

3) A lot of acoustic sensors. Concerns here. Should investigate further.

Potential mitigation measures
- Directional antenna not a feasible solution on water, since the constant swaying motion of buoy will be problematic. Have seen work at GTRI using switched beam antenna to compensate for the pitch-roll motion of the platforms.

- Distance will be the only safe buffer for buoys. Fortunately, most buoys are quite far offshore. The only exception is C-MAN stations, but they use directional antennas, which helps mitigate interference.

(Additional comments)

- Greater concern about acoustic sensors (lowest frequency of interest is 9KHz).

- Large no. of organizations with buoys (National Ocean Service). Canadians. Will provide slide on partners. However, they are probably quite similar to the US.

- Buoy networks also in Europe (UK Met, use MeteorSat (geostationary) in place of GOES).

Summary of main concerns:

- multipath interference from wind farms on GOES for the weather buoys.

- Acoustic sensors.

-- OTHERS#1 ---

(Offshore wind farms)

Identify the system
WERA (WavE RAdar)

- Phased array. Digital beamforming on receive. Tx has +-60 deg beam (4-element square with passive directors).

- Scatters off surface ocean waves that are ½ the radar wavelength. 1st order returns: currents and wind directions. 2nd order returns: wave signatures like directional wave spectra.

- 1 system at 12MHz, 3 systems at 16MHz. Tx 30-35 Watts. Coverage out to 120km. FMCW. Bandwidth 100KHz (1.5 km range resolution).

- Relies less on software processing. CODAR relies on software intensive processing (MUSIC).

- Purchased through ONR grant in 2004 for Southeast ocean observing. Part of IOOS HF network (8-9 WERAs in the network).

- Angular resolution down to a few degrees in ocean current mapping with 16 receive antennas.

- Tx-Rx are spatially separated to avoid self jamming (by distance or elevate Tx antenna)

- Does not operate on multistatic mode.

- Low-res data are fed to the NOAA network. Hi-res data are brought back on hard disk.

Types of interference

- Depends on Doppler noise frequency. Whether it gets into Doppler Bragg spectrum (around 0.4Hz).

- Need to do some research to find the answer.

- May affect the 2nd order return more than the 1st order return. The 1st order returns (currents) are what IOOS network is looking for and reports. The 2nd order returns contains more detailed wave information.

- PRF at 0.26 sec (or about 4Hz). (the turbine Doppler clutter will be badly aliased in their system.)

Potential mitigation measures
- Beamforming can resolve and isolate wind farms in azimuth, provided the farms are not so close to the radar to create blockage.

- Discussed the possibility of taking in-situ measurement of a land wind farm to get an idea of the type of interference on WERA. Takes a week to set up a WERA system on-site.

-- OTHERS#2 --

(Offshore wind farms)

- Offshore wind developer. Formed by leaders of the commercial fishing industry in NJ. In charge of site assessment -- prospecting sites, wind resources, biological resources, geophysical and geotechnical survey, presence of birds and bats, and permitting efforts.

- Close to commercial fishing industry. Owners own commercial fishing companies.

- Aware of: potential for turbine arrays masking the presence of other vessels and objects on the water. That is the only concern commercial fishermen have in regard to electronics.

- Q: Is this a big/frontline concern? Not sure about priority. Greatest concern: would be prevented from fishing in areas occupied by turbines. E.g. CG would exclude them from fishing in areas where they normally fish. “Set exclusion zone in order to ensure safety?” That would be a tough requirement to implement… Shutting off a whole area of the ocean… A lot of stakeholders. Not going to fly.

- As wind developers: We have no intention to prevent fishing in wind farms. Under sea bed there are scour protection from turbine foundation (50-100’). Make fishermen aware of this so they proceed with caution. Aligning turbines so that there can be a long tow at the same water depth. Won’t interfere much with fishing (could maintain constant depth in straight-line tows).

- Q: Artificial reef. Yes.

- Q: current projects? Two under way. 25MW, 6 turbines in state waters Atlantic City, NJ. Due to start construction in 2014. 350MW utility scale farm off federal waters off NJ coast. Working with BOEM to look at other areas under development from S. Carolina to Maine.

- Q: Will environmental assessment continue? In federal water, BOEM will perform initial environmental assessment. Make information available to developers. To gain permits, developers have to conduct a series of pre and post construction monitoring programs (birds, marine mammals, bats, sea critters living in seabed). Conduct BACI (before after control investigation). Establish control area. Do assessment in both control area and project area. To assess if any impacts in the environment and biology.

- Q: Can tests be done on navigation equipment, similar to BACI? Could do this. Who might fund this? US Army Corp. of Engineers, NOAA, CG, DOE.

- Q: BACI a well set of procedures? Yes. State waters project. Well under way. Will provide design, and Fish & Wildlife and National Marine Fishery Service will give feedback. Require the developers to quantify the impact of the project.

- Q: What about SONAR? Commercial fishing boats operate fishing boats? Need to look at frequency (5-20KHz). Suggestion: compare frequency against operating frequency of the sonar equipment (sounders and fish finders).

- Q: Commercial fishing group as a stakeholder: has this navigation interference issue come up? Yes, it has been discussed during public comment and application review for their project. Everyone recognize and agree that there will be interference. But there were no strong objections from the commercial fishing group. (This does not mean it will not happen to other developers in other projects.) “Fishermen speak from their heart and don’t dance around with words.” But they recognize the need for renewable energy to be developed, and are willing to make sacrifices. Just need to navigate through it or around it.

- No other entities similar to Fishermen’s Energy. Mid-Atlantic and Northeast.

- Commercial fishing contacts: organized by region or ports (Alliance of fishermen’s group). Tend to be fragmented.

- Q: How about recreational fishing area? Organized group? A: Clubs based on ports or harbors. They are usually in support of wind farms, because they think they will create habitats and enhance fishing. Navigation not as much of an issue, because they usually go out during the day and don’t have sophisticated equipment.

- Q: Ferry boat operators. A: CG will usually be in charge of this. Ship passage routes for tugboats, barges, major sea lanes are long established. BOEM will not approve leasing blocks for wind farms near these areas. BOEM will be working closely with the CG on this.

(Additional comments)

- Summary: People recognize there will be interference to navigation equipment. But have had no objections (from CG, commercial fishing industry, recreational boaters, maritime transportation industry) during the public comment period.

B2. ACOUSTIC SYSTEMS

B2.1. Methodology

Technical information and opinions on the potential of noise generated by wind turbines interferring with marine acoustic systems were collected from a wide range of stakeholders by conducting personal interviews. These interviews were carried out to understand their past experiences with acoustic interference and to identify potential stakeholder concerns regarding radiated noise from future offshore wind farms.

Contact with stakeholders was made through one of several methods. The primary means of contacting stakeholders was by an email campaign, in which the following attachments were sent: 1) a letter of introduction from the DOE; 2) a background letter from the University of Texas; and 3) a list of talking points. The percentage of respondents to these inquires was small, and remained so even after repeated attempts to contact stakeholders at various levels in their organizational structure via email. In an attempt to improve the number of respondents, the initial contact was modified to include other methods, such as a greatly abbreviated initial contact email that in two very short paragraphs provided a brief summary of the stakeholder survey project and requested the recipient's cooperation. In this approach, the only attachment was the DOE letter of introduction.

Additional methods of contact included phone calls to individuals or offices in government agencies or private companies, as well as interviews with potential stakeholders with whom the investigators have had prior professional contact. Section B2.2 is a list of stakeholders that agreed to an interview. In most cases, those who agreed to participate were interviewed using a written questionnaire as guiding talking points. The questionnaire-formatted interviews were semi-structured, with broad and open-ended questions to allow for a more stakeholder-centric view from the interviewees. The guiding questions used on the interview are included in Section B2.3. Some stakeholders had strong opinions about the technical areas important to them, and in such cases it was best to abandon the questionnaire format and let them pursue their line of discussion while insuring that the salient points for the stakeholder survey were covered.

The interviews lasted from 90 minutes to as little as 15 minutes. Interviews were conducted over the phone and in a few cases in direct meetings (face-to-face). Immediately after each interview, key notes taken were summarized in written form. A summary of the interviews is given in Section B2.4.

B2.2. List of Participants[2] (Arranged by Category)

Dr. George Ioup	Department of Physics University of New Orleans 2000 Lakeshore Dr., SC 1021 New Orleans, LA 70148 Marine Mammal Research and Monitoring

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[2] The titles and affiliations of the interviewed participants are those they held at the time the interviews were conducted.

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Marine Mammal Research and Monitoring

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Mr. Rodney Nelson	Vice President Government &Community Relations Schlumberger 210 Schlumberger Dr. Sugar Land TX 77478 Oil and Gas Exploration
Mr. Ricky Bailey	Senior Engineering Scientist Advanced Sonar Division Applied Research Laboratories The University of Texas at Austin PO Box 8029 Austin, TX 78713
Ms. Melissa Sanderson	Chief Operational Officer Cape Cod Commercial Hook Fisherman's Association 1566 Main Street Chatham, MA 02633 Commercial Fishing Industry
Dr. Joseph Rice	SSC San Diego Engineering Acoustics Chair Department of Physics Graduate School of Engineering and Applied Sciences Monterey, CA 93943

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B2.3. Stakeholder Questionnaire/Talking Points for Acoustic and Seismic System

The objectives of this questionnaire are to 1) support the DOE initiative in identifying the potential for offshore wind farms to interfere with acoustic sensors and electronics as outlined in the attached letter and statement of work; 2) establish a dialogue with potential stakeholders to communicate related operational and technical issues; and 3) provide a baseline of information for follow-up communication via e-mail, phone calls, or meetings.

Background**:** This survey is focused on wind-farm noise below the 2-kHz range that may radiate underwater. In this frequency range, the noise contains both tones and broadband components. The following questions pertain to any acoustic sensors, passive or active, operating at frequencies below 2 kHz.

Note: Some stakeholders may not be able to respond to this questionnaire specifically or in detail because of proprietary (commercial) or classified (government) specifications. Please respond in as much detail as possible.

In your experience, have any of your sensors or systems been adversely affected by background noise from any source at frequencies below 2 kHz?

YES ___ NO ___

Comments:

Do you have any concerns that future stakeholder systems may be affected by wind-turbine generated noise?

YES ___ NO ___

Comments:

If your system is an active sonar, what type of waveforms do you transmit, and at what source level and frequency?

Waveforms _________ Source Level _________ Frequencies _________

Comments:

If your system is passive, what is the frequency band of your sensor or signals of interest?

Waveforms _________ Source Levels _________Frequencies _________

Comments:

What type of signal processing does your system employ for noise reduction and/or detection?

Comments:

What is your sensor configuration? Please check the appropriate configuration and enter further information in the space provided.

Omnidirectional ___ Directional hydrophone ___

If array, number of elements and geometry ________________________

Number of elements used in forming a single beam ________________________

Comments:

In what depth of water do you typically operate your system and at what depth do you deploy the sensor?

Range of water depths (sea floor) in which system is operated

____

Range of sensor deployment depths ________________________

Comments:

Does your system operate as a fixed (in position) or is it mobile as in a towed array?

Fixed position ___ Mobile ___

Comments:

If it is fixed is it moored, bottom lying, or is it attached to a structure.

Moored ___ Bottom lying ___ Attached ___

Comments:

If your system is directional, is it typically steered for maximum sensitivity in the vertical or the horizontal direction?

Vertical steering ___ Horizontal Steering ___

Comments:

At what range scales does your active system operate?

Range: ________________________

Comments:

Is the performance of your system impacted by weather related phenomena such as high seas or wind?

Yes ___ No ___

Comments

Can you think of anyone else we should talk to about this?

Within your organization?

Outside your organization?

Sonar systems?

Before we conclude our interview, is there anything else that you think we should consider?

Thank you for taking the time to share your opinions.

B2.4. Interview Notes

Marine Mammal Monitoring

Dr. Juliette and Dr. George Ioup, UNO
Dr. Grayson Rayborn, USM
Sensor Type – Omni EARS Buoy
Frequencies range of interest - 500 Hz to 90 kHz

Juliette and George Ioup, physics professors at the University of New Orleans have, in collaboration with several other universities, conducted marine mammal acoustic measurement and research for about 10 years. The interview was very informative and the discussion ranged from the frequency band and waveform of "clicks" transmitted by various marine mammals, to signal processing techniques to improve data quality. Also discussed were sensor design and deployment methods and locations.

The Ioups' focus is primarily on acoustic monitoring of whales and porpoises using an omni-directional sensor called EARS. The EARS buoy is deployed underwater at a depth of 50 to 250 m off the bottom in depths from 600-1800 meters. To support monitoring of different species, signal processing is broken up into three frequency bands of interest contained in the range from 500 Hz to 90 kHz. Depending upon proximity of wind farm to the observation area, noise from wind farms may very well contaminate acoustic recordings used in this research. However, it is expected that the signal processing algorithms currently used will sufficiently mitigate the contamination that it will not affect the research and its results in a significant way.

Dr. Rayborn is a physics professor and department head (Ret) at the University of Southern Mississippi and participates in the above-mentioned collaboration with the Ioups. Dr. Rayborn's views on all salient points reflected those of the Ioups, but it was interesting to hear a different perspective.

The consensus was that it is very unlikely that the radiated noise transmitted from wind farms will significantly impact their research.

Dr. Christopher Tiemann
Sensor Type – Omni EARS Buoys and similar systems custom made at ARL.
Frequencies range of interest - 500 Hz to 90 kHz

Dr. Tiemann is a research Scientist at the Applied Research Laboratories, The University of Texas at Austin, sponsored by the National Science, and makes his own sensors or uses EARS buoys similar to those used by the collaboration mentioned above between UNO and USM.

Since this project has only deployed sensors near coastal areas in the U.S., it has not encountered any wind-farm-generated noise at this time. However, other man made sources of noise such as shipping and offshore oil production are evident in the measurements from these sensors. This project is not concerned about potential interference from wind farms because the researchers are confident that either their signal-processing algorithms will filter out unwanted signals, or they will be able to distinguish them from whale vocalizations.

This project deploys measurement systems that are moored above the sea floor in a water depth of 500 m or greater, similar to the EARS deployments previously described. The above-mentioned signal processing, along with attenuation of wind farm acoustic signals with range, minimizes the likelihood that there will be a problem. These measurements are impacted by weather-related phenomena, but good results can be obtained at moderate sea states.

Acoustic Research and Development, Office of Naval Research (ONR)

Mr. Raymond Soukup
Sensor Type – ONR conducts research and development for a large variety of active and passive acoustic systems
Frequencies range of interest – full range of ocean acoustic systems 0 Hz – 200 kHz and higher

ARL:UT exchanged several emails and had several telephone conservations with Raymond Soukup, Ocean Acoustics Program Officer in ONR 32, who coordinated the response to the wind farm inquiry for the Office of Naval Research. Mr. Soukup discussed the information provided by ARL:UT with Dr. Robert Headrick, head of the Ocean Acoustics Team, and Dr. Frank Herr, ONR 32 Department Head (SES).

The ONR consensus is that since they have flexibility in choosing locations for testing and evaluating emerging technologies, they can simply choose areas where background noise will not be a problem.

Marine Seismic Surveys for Oil and Gas Exploration

Dr. Craig Beasley, Schlumberger; Mr. Shawn Rice (VP Operations) and Mr. Dale Lambert, ION Geo-Ventures
Sensor Type – Marine seismic arrays – typical multiple parallel line arrays towed behind a ship
Frequencies range of interest – 0 Hz to 500 Hz

Dr. Beasley is with Schlumberger, and Mr. Lambert is with ION Geo-Ventures are seismic experts representing their respective companies. These stakeholders were interviewed separately and the following is a combined summary of the two interviews.

Critical factors of interest: location and distance of wind farms from seismic survey areas; the environmental acoustics in terms of the propagation conditions between wind farm location and seismic survey location; and spectral characteristics of the interfering noise. They are also interested in knowing where future wind farms are likely to be built and what the likely spectral characteristics or noise level versus frequency will be.

The oil and gas seismic exploration industry has some concerns regarding interference from wind farms, but a number of mitigation techniques are available, including band pass filtering or wavelet processing using Riker wavelets.

There are also some concerns about the ongoing trend for regulatory government agencies to establish "acoustic noise budgets" for the combined underwater noise from all sources, including noise from natural sources. Wind farm noise may compete with proposed seismic surveys for the limited acoustic budget.

Marine Seismic Surveys for Geophysics Applications

Dr. Cliff Frohlich, Associate Director, UT Institute for Geophysics
Sensor Type –
Frequencies range of interest – 0 Hz to 500 Hz

Dr. Frohlich's expertise is in the analysis and interpretation of seismic data, and focuses primarily on applications in geophysics. In our discussion, he summarized typical sources of background noise that have the potential to interfere with analysis of seismic signals of interest. The following comments assume that the seismometer of interest is not collocated with the wind farm and is at a "distant" location.

For most propagation environments, seismic signals with frequencies greater than 20 Hz are attenuated in the propagating media (seafloor) over long distances. At frequencies less than 1 Hz, breaking ocean waves usually dominate the spectrum even at the most interior regions of a continent. Since breaking, creaking waves dominate over most industrial noise, it is unlikely that offshore wind-farm noise would contribute to noise in this frequency band.

In general, there could be wind farm noise in the signal band of interest to seismologists, but in most cases mitigation using standard signal processing methods will likely be effective while, in some frequency bands, other sources of noise are likely to dominate the spectrum.

Commercial Fishing

Ms. Melissa Sanderson, COO, Cape Cod Commercial Hook Fisherman's Association
Sensor Type – Directional Active Sensors
Frequencies range of interest – 30 kHz to 200 kHz

After many attempts to contact this organization through email, initial contact was made via telephone with Melissa Sanderson, COO of the Cape Cod Commercial Hook Fisherman's Association. Ms. Sanderson was busy with a fund-raiser and asked me to email another copy of our detailed contact package and she would forward it to their organizations technology representative. In a follow up telephone conversation, Ms Sanderson indicated that she did not anticipate a problem with noise from wind farms, but would consult the organization's technical representative and contact us if there were any issues they are concerned about.

Mine Warfare

Mr. Ricky Bailey, ARL:UT, Program Manager for Mine Detection and Classification research and development.
Sensor Type – Directional Active Sensors
Frequencies range of interest – 20 kHz to 1.5 mHz

This project is sponsored by ONR Code 32 and is “fast tracking” technology for detecting and classifying mines in high clutter environments. Sensors include towed, hull mounted, and possibly helicopter-dipping sonar systems. Industry collaborators in the US include Raytheon and Northrop Grumman’s North American division, and the Navy sponsor of this program in PMS 495. European collaborators include BAE and Thompson.

Mr. Bailey’s opinion is that, given the design characteristics, acoustic frequencies, signal processing techniques, waveforms, and probable deployment strategies utilized for mine detection and classification, these systems are not likely to experience interference from wind-farm-generated noise.

Swimmer Detection

Mr. Kenneth Krueger, Project Manager, Advanced Technology Laboratory, ARL:UT, Program Manager for Mine Detection and Classification research and development.
Sensor Type – Directional active Sensors
Frequencies range of interest > 80 kHz

Mr. Krueger’s opinion is that swimmer Detection sonar > 80 kHz used by the U.S. Coast Guard’s (USCG) Maritime Safety and Security Team (MSST) for port security is very unlikely experience interference from wind farms due to the very high acoustic frequencies, likely locations for deployment, and methods of operation.

Monitoring Maritime Traffic

Gary Wilson, ARL:UT, sponsored by DHS and DOD
Sensor Type –
Frequencies range of interest – 10 Hz to 25 kHz

Dr. Wilson is conducting research and development that is focused on underwater acoustic monitoring of maritime traffic. His work utilizes narrow band (spectral lines) and broad band noise to monitor a broad range of marine vessels. This system uses processing that can distinguish between marine traffic and unwanted industrial noise such as wind turbine noise.

Existing signal processing in acoustic marine traffic monitoring systems is expected to provide sufficient mitigation to interfering signals such as wind turbines.

Sub-Bottom Profilers

Dr. Nicholas Chotiros
Sensor Type – Directional Sensors
Frequencies range of interest - 1.5 kHz to 6 kHz

Sub-bottom profilers may be towed behind a research vessel or hull mounted, and are used to create vertical profiles of the sea floor and map sediment layers down to a sediment depth of 10-100 m.

Specifications may vary but a typical sub-bottom profiler pulse is a chirp 20 to 50 milliseconds in length that sweeps from low frequency to high frequency in a band of approximately 4 kHz. The specifications do vary, but an example of a typical sub-bottom profiler pulse might sweep from. Some profilers, designed to get the best resolution and penetration in a variety of sediments, have two pulses in different bands. This might include a low frequency band sweep from 1.5 to 5.5 kHz and a high frequency band sweep from 3 kHz to 6 kHz.

Given the vertical directionality, the frequency range, and the pulse design of sub-bottom profilers, it is highly unlikely that noise from wind farms will interfere with sub-profiler technology.

Department of Defense – Blanket Statement for all Systems

Mr. Frederick C. Engle
Sensor Type – all acoustic systems and sensors
Frequencies range of interest – all bands

Mr. Engle was the official representative for the Department of Defense (DoD) in responding to the stakeholder acoustic questionnaire. Offshore wind farms are relative newcomers to marine noise environment and, because the details of systems of interest to the DoD are frequently classified, the details of what can and may be said about this subject tend to be, necessarily, obfuscated.

Mr. Frederick’s response was “You'll note that most of these questions cannot be answered and this is because any response to these questions would be classified. The bottom line here, as indicated in the responses to questions one and two, is that we don't know enough about the amount of underwater noise that will be radiated from offshore wind turbines. Hopefully your research will give us that information.”

Appendix C
Details on First-Principle Modeling

This appendix describes the details of our effort to provide a baseline assessment of potential impact of offshore wind farms on electronic systems based on first-principle electromagnetic and acoustic modeling. Earlier, electronics systems typically encountered in sea surface operations, airborne missions, and sub-surface operations were first identified. Subsequently, detailed personal interviews with several key stakeholders were conducted to identify the full range of concerns on the effect of offshore wind farms on these systems. For this task, we first identify those systems that are potentially most susceptible to offshore wind farm interference and yet have been least studied thus far. This ensures that we devote our resources in this project to the most important issues, while not duplicating past or ongoing efforts in this area. Section C1 of this appendix summarizes our modeling effort in electromagnetic systems. Section C2 summarizes our effort in acoustics systems.

C1. ELECTROMAGNETIC SYSTEMS

The electromagnetics modeling effort focused on several key cases identified through stakeholder interviews. These cases include marine radar, airborne radar, HF radar, and communications systems. It is worthwhile to point out that there are other systems of concern such as land based radar systems used in long-range surveillance, air traffic control and weather. However, there are currently other efforts to address these concerns. Processes are in place to evaluate the impact of land-based wind farms on these systems. It is believed that these existing processes can be readily extended to address future offshore wind farms. Therefore, they are outside the scope of the present study. Below, detailed descriptions of the four case studies are reported.

Appendix C1.1

Modeling Study on the Effect of Offshore Wind Farms on Marine Radar

1. Scope of Study

This study was performed to simulate the effect of offshore wind farms on marine radars installed on boats and shipping vessels. The radars considered are commonly installed systems operating in the S- and X-Band. Modeling was performed for a generic class of radars operating in these bands. Although no vendor-specific radar processing was performed, the modeling results should provide a representative baseline evaluation. There have been several modeling and measurement studies to study the effects of wind farms on marine radar performance [1], [2].

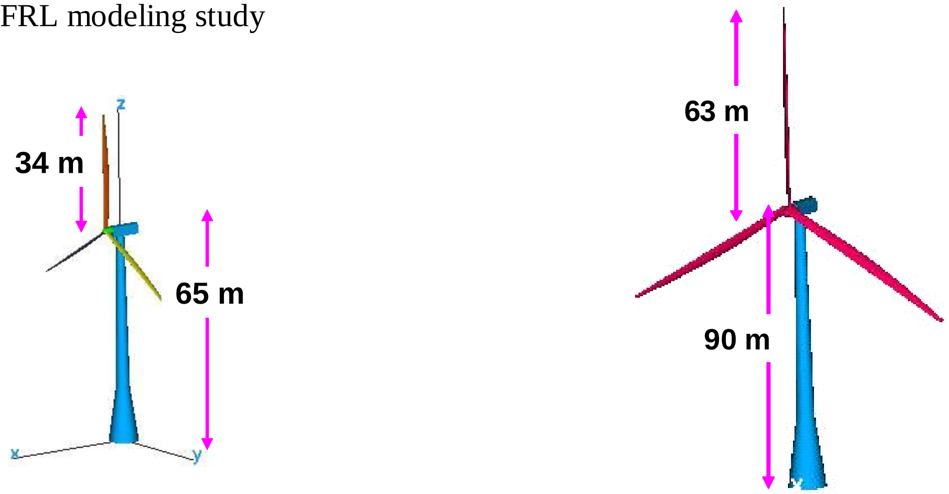
2. Details of Study

The study was performed in two parts. In the first part of the study we simulated and studied the radar cross section of wind turbines and boats in the two bands of interest. In the second part of the study we modeled the radar performance for the targets of interest accounting for the RCS and propagation loss on ocean.

Two CAD models of wind turbines were used in the simulation. The first CAD model was of size representative of land-based wind turbines as reported in AFRL report [3]. This model was studied in detail by AFRL and published simulation and measurement data [3]. The other wind turbine is the NREL model. This wind turbine was described in the document [4].

2.1 RCS and Doppler Modeling of Wind Turbines

Modeling was performed using the Xpatch Code [5]. Xpatch is based on high-frequency ray-tracing on the computer model of a complex scene [6]. The simulation algorithm in Xpatch is based on the Shooting and Bouncing Ray (SBR) technique. This technique is based in part on the theory of geometrical optics (GO), which states that optical laws may be formulated in the language of geometry when the wavelength of an electromagnetic wave is very small relative to the structure of interest. Geometrical optics (GO) is implemented by illuminating an object with rays that can be traced through the geometry. In homogeneous media, the rays travel along straight paths and, at material discontinuities, their behavior is governed by the Fresnel formulas along with Snell’s laws of reflection and refraction. This procedure is referred to as ray tracing. Unlike traditional GO, however, when the rays strike a target a small amount of current is painted at the hit point in Xpatch. After the entire scene is traced, all of these currents are radiated to find the returned signal of interest. The Xpatch code has been validated extensively against measurements on aircraft and ground vehicles. The code is maintained by SAIC for the US Air Force and has been distributed to over 450 user groups.

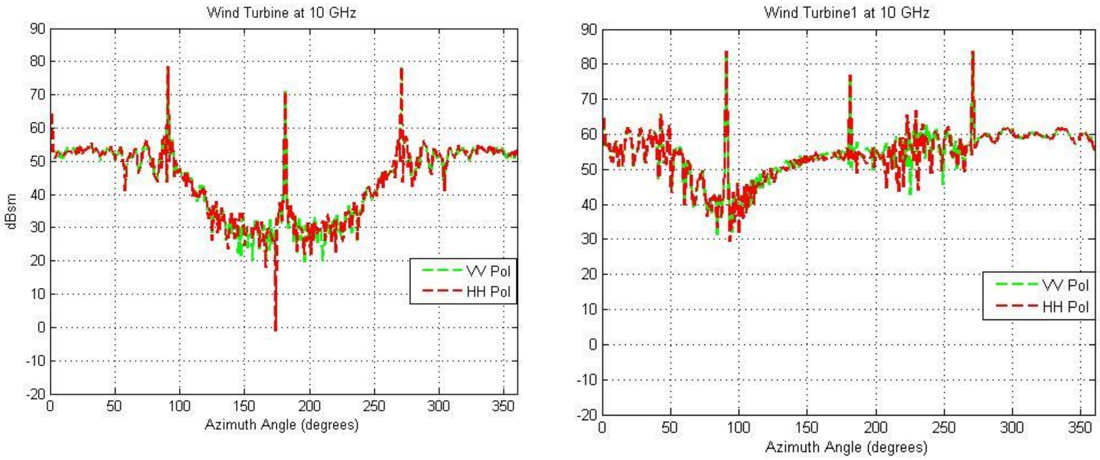


(a) CAD Model similar to AFRL modeling study

(b) NREL CAD Model

Fig. 1. AFRL and NREL Wind Turbine Models

Fig. 1 shows the CAD model for the two wind turbine used in this study. These CAD were designed based on the wind turbine parameters published in the AFRL report [3] and the NREL report [4]. The AFRL representative wind turbine CAD model (Fig 1(a)) has a blade length of 34 m and a height of 65m. The NREL wind turbine CAD model has a blade length of 63 m and a height of 90 m. Fig. 2 and Fig. 3 show the RCS prediction at S-band and X-band for the two wind turbines.

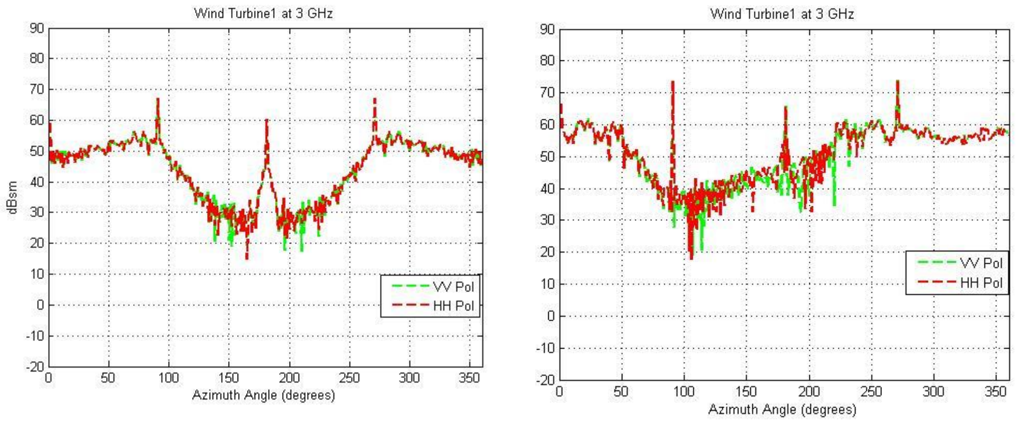


(a) **AFRL Turbine**

(b) **NREL Turbine**

Fig. 2. Wind Turbine RCS at 10 GHz. (a) RCS prediction for AFRL model at EL=0^o. (b) RCS prediction for NREL model at EL=0^o.

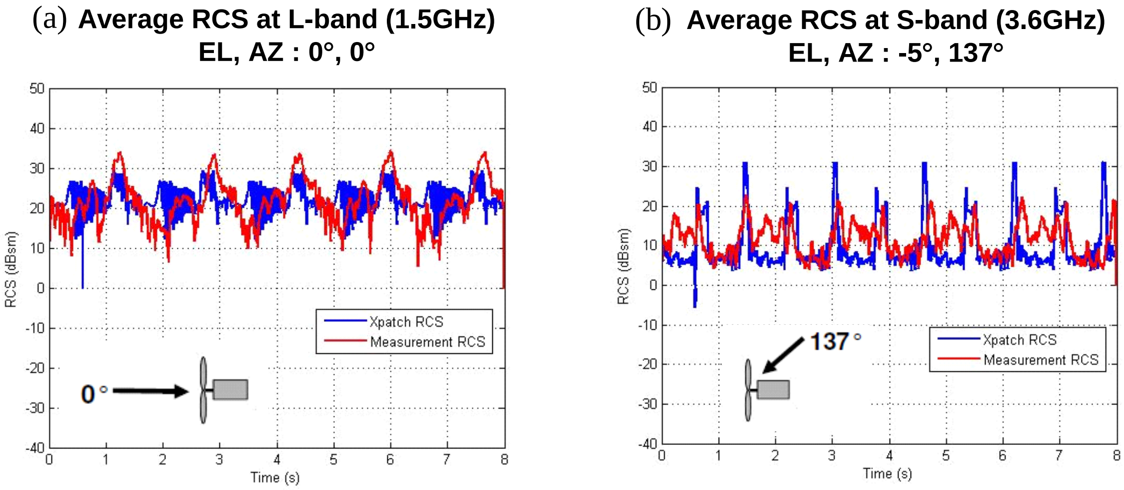
The predictions were carried out at an elevation angle of 0^o over a 360^o azimuth scan. Both the VV and HH polarization of the RCS are plotted in the figures. The NREL wind turbine has a bigger dimension and hence has a higher RCS as compared to the AFRL wind turbine model. The RCS results show specular flashes from the individual blades at specific azimuth angles.


(a) **AFRL Turbine**

(b) **NREL Turbine**

Fig. 3. Wind Turbine RCS at 3 GHz. (a) RCS prediction for NREL model at EL=0^o. (b) RCS prediction for NREL model at EL=0^o.

In 2007 AFRL performed an Xpatch validation on wind turbines to determine if Xpatch can predict RF effects from wind turbines with sufficient confidence [3]. This would avoid the need for extensive field testing of new wind farms. The validation was performed at L, C, S and X bands at multiple azimuth and elevation angles. The AFRL validation exercise concluded that Xpatch predictions can accurately predict RCS. In addition, the knowledge of radar systems is crucial in determining prediction accuracy requirements. Using the AFRL representative CAD model and AFRL published measurement data [3] we were able to perform a validation of our Xpatch predictions. Fig. 4 shows the comparison between Xpatch and AFRL measurement data at L-band and S-band at two different elevation and azimuth angles. The predictions were performed for a blade spinning at 12 rpm. The Xpatch predictions were performed at various time snapshots in the 8 second time interval. There are 24000 snapshots in the 8-second interval of data shown in Fig. 4. The total Xpatch computation run time was 48 hrs on a desktop linux workstation. The comparison between the Xpatch RCS prediction and measurement is reasonable considering the differences between the CAD model and the actual measured wind turbine. This comparison gives us the confidence that Xpatch can provide sufficient accuracy to asses wind farm interference effects on radar systems.


(a) **Average RCS at L-band (1.5GHz) EL, AZ : 0°, 0°**

(b) **Average RCS at S-band (3.6GHz) EL, AZ : -5°, 137°**

Fig. 4. Comparison between Xpatch RCS predictions and AFRL measurements. The comparison was done for a spinning wind turbine at various time snapshots. (a) L-Band comparison, (2) S-band comparison.

The simulation methodology to generate Doppler spectra of a rotating target requires the computation of the scattered field at different time snapshots of the target as the moving part undergoes motion. The resulting time-varying scattered field is then Fourier transformed to arrive at the Doppler spectrum. From the SBR simulation perspective, each time snapshot on the target with a different moving part position is a new electromagnetic problem and requires that the whole computation be carried out from scratch. To validate Xpatch Doppler spectra predictions, AFRL measurements [3] were used. AFRL measurements were taken from a rotating wind turbine. The dynamic RCS data were processed using the short-time Fourier transform to generate a time-frequency plot, as shown in Fig. 5(a). The time-frequency plot shows the evolution of the Doppler spectra as a function of time as the wind turbine blades turn. Every time the wind turbine blade is perpendicular to the radar of line of sight (LOS) it generates a Doppler flash. There is a positive and negative Doppler flash depending on whether the blade is moving towards or away from the radar. Between the negative and positive Doppler flash is the sinusoidal curve due to the diffraction from the blade tip. This pattern repeats itself for each blade and there are three such patterns in a complete blade revolution. The Xpatch prediction for the AFRL wind turbine is shown in Fig. 5(b). They show a similar pattern that matches the measurement Doppler spectra. The Doppler spectra comparisons were done at L-band for an 8 second collection period. 24000 Xpatch snapshots from the simulation are used. The measurements show a much thicker zero-Doppler line which runs horizontally in the middle of the plot. This shows there was significant stationary clutter in the collection. This was not modeled in the Xpatch simulation.

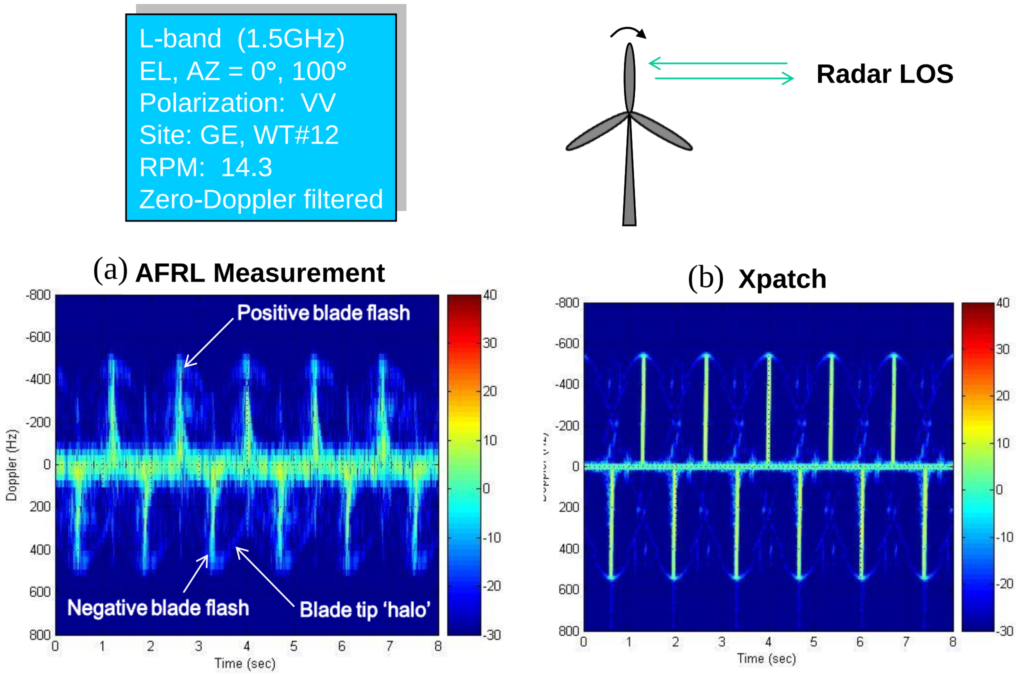


Fig. 5. Comparison of Doppler spectrum between AFRL measurements and Xpatch simulations at L-Band. (a) AFRL measurement, (b) Xpatch simulations.

2.2 RCS Modeling of Boats

We obtained a CAD model of a generic fishing boat to model its RCS. This CAD model and the associated predictions are shown in Fig. 6. The Xpatch predictions were carried out at X-band and S-band for an elevation of 0^o degree and a full azimuth scan. The RCS is dependent on the azimuth angle due to the structure of the boat. The sides of the boat contribute to RCS peaks in the data. A peak and nominal (average) RCS can be extracted from this data. In our study the nominal RCS values for our subsequent modeling. A marine radar will encounter a range of boats and with varying sizes. Technology Service Corporation [1] carried out a RCS modeling on the various class of boats. Table 1 is reproduced from the TSC report and shows the peak and nominal RCS for different boats. For some of the larger class of boats (e.g oil barrages) their RCS can be comparable to that from a wind turbine shown in Fig. 4.

Boat RCS can be comparable to the Wind Turbine RCS

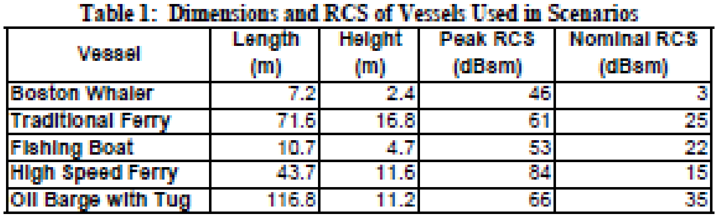


Table 1: Dimensions and RCS of Vessels Used in Scenarios

Vessel	Length (m)	Height (m)	Peak RCS (dBsm)	Nominal RCS (dBsm)
Boston Whaler	7.2	2.4	46	3
Traditional Ferry	71.6	16.8	61	25
Fishing Boat	10.7	4.7	53	22
High Speed Ferry	43.7	11.6	84	15
Oil Barge with Tug	116.8	11.2	66	35

Table 1. Peak and Nominal RCS for various boats as reported in Reference [5].

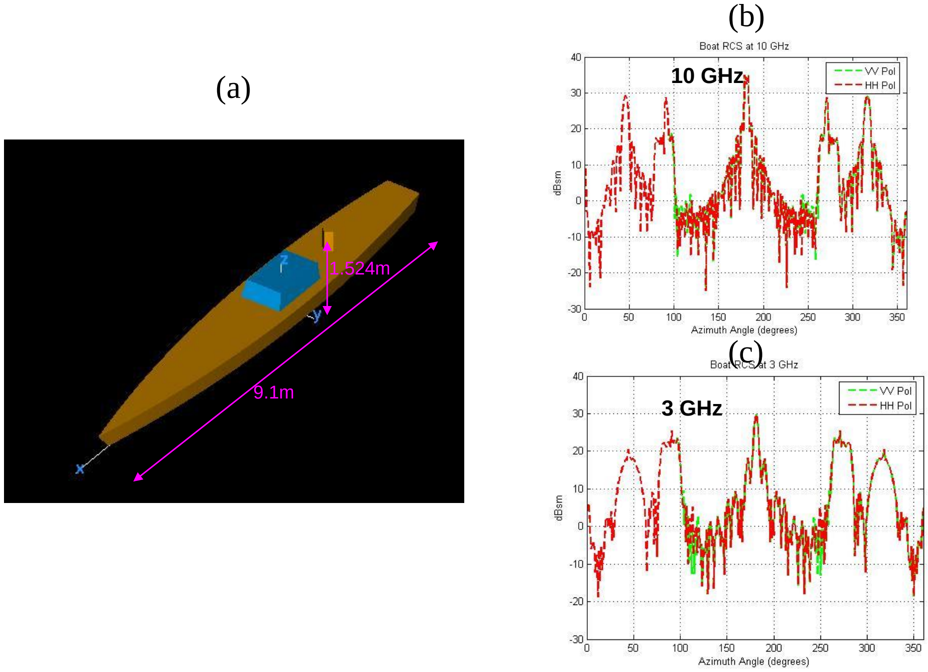
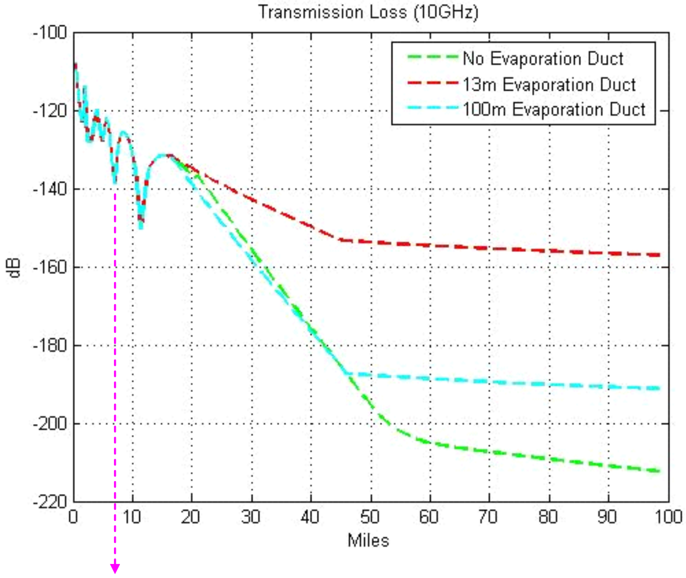


Fig. 6. Xpatch RCS prediction for the boat. (a) The CAD model and dimensions of the boat. (b) X-band predictions. (c) S-band predictions. The nominal RCS is comparable to the fishing boat as reported in Table 1.

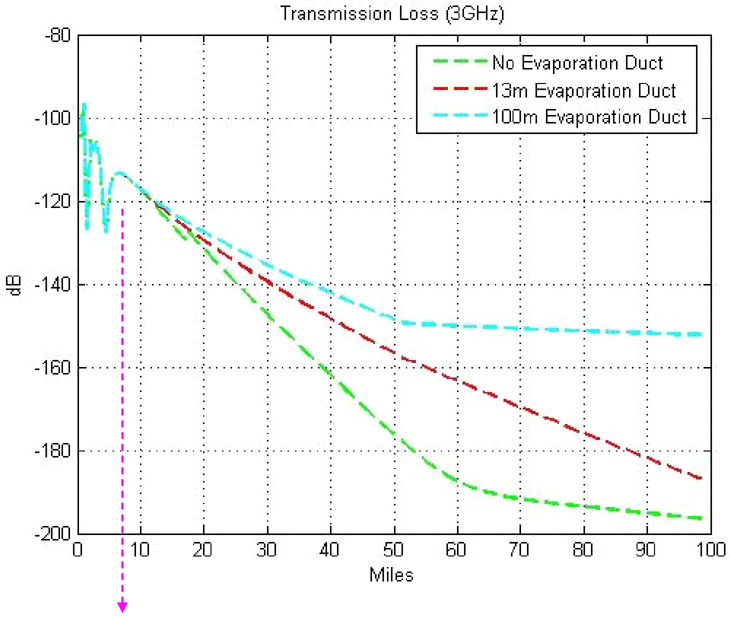
2.3 Modeling of Propagation Over Ocean

We used Engineer's Refractive Effects Prediction System (EREPS) model [7] to assess the electromagnetic propagation effects of the lower atmosphere on radio wave propagation. The EREPS models accounts for the effect of optical interference, diffraction, troposphere scatter, refraction, evaporation and surface based ducting and water vapor absorption under horizontally homogenous atmospheric conditions. Fig. 7 and Fig. 8 show the X-band and S-band propagation transmission loss for three different evaporation duct scenarios respectively. The evaporation duct does aid in the transmission of radio waves in the long separation distances between transmitter and receiver but in the near end optical region (< 10 miles to the receiver) the evaporation ducts do not assist in the transmission. The EREPS model is developed and distributed by US Navy and details of the EREPS models are available in [7].



No effect in close by optical region

Fig. 7. RF propagation loss over ocean for three different evaporation duct scenarios at X-band. There was no effect on propagation from the evaporation duct in the optical region.



No effect in close by optical region

Fig. 8. RF propagation loss over ocean for three different evaporation duct scenarios at S-band. There was no effect on propagation from the evaporation duct in the optical region.

2.4 Radar propagation and PPI modeling

We developed a radar modeling tool to access the effect of wind turbines on marine radar. The various parts to the radar model are listed in Fig. 9. The target RCS database for wind turbines and boats was simulated using Xpatch. EREPS was used to model the propagation loss over ocean surface. A set of standard antenna beam patterns were chosen for the simulation. A Plan Position Indicator (PPI) display was constructed using the received radar signal. The received radar signal was converted to a PPI display after choosing an appropriate threshold level. The PPI display was used to access the effect of wind turbines on marine radar systems.

Radar Signal Received = Antenna Beam Pattern (Tx and Rx) x Propagation Loss Over Ocean x Target RCS (Wind Turbine, Boat)

Fig. 9. The various components of the radar modeling tool used to model the radar signal received.

3. Scenarios and Modeling Results

We selected two scenarios for modeling the effects of boats in the vicinity of wind farms. The first scenario was described in the TSC report [2], which was specifically conducted to address the Cape Wind project in Nantucket Sound. The second scenario was provided by DOE using the NREL wind turbine configurations. The Nantucket Sound wind farm configuration is shown in Fig. 10. The wind farm consists of 150 wind turbines distributed over a 10 square kilometer area. The average separation between the wind turbines is around 1 km. The dynamic scenarios involved a marine radar mounted on a Coast Guard vessel as it moves in the vicinity of the wind turbines as shown in Fig. 10. The marine radar track is marked in red and moves horizontal to the wind farm. The Boat 2 track marked in purple moves inside the wind farm and final exits the farm. The Boat 1 track marked in blue stays outside the wind farm. 100 PPI frames for the scenario were simulated.

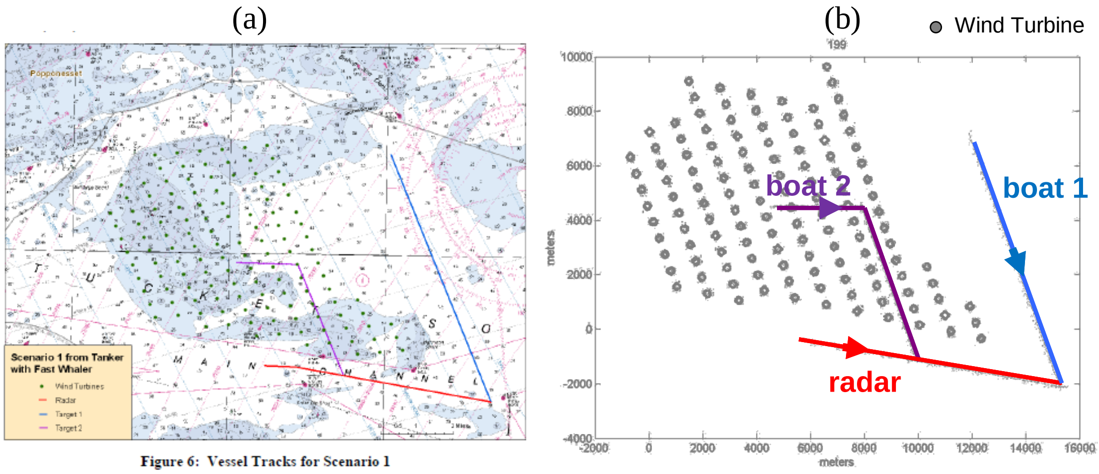
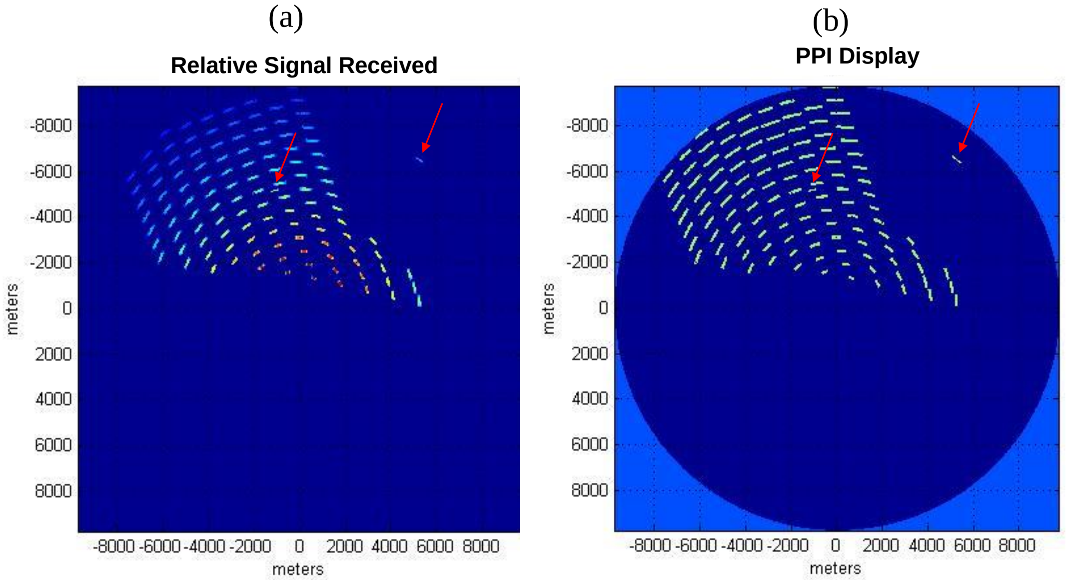


Fig. 10. Wind farm configuration scenario used for Nantucket Sound radar modeling. (a) Figure from report showing the wind farms, boats and radar movements. (b) The wind farm configuration used in this study.



Relative Signal Received

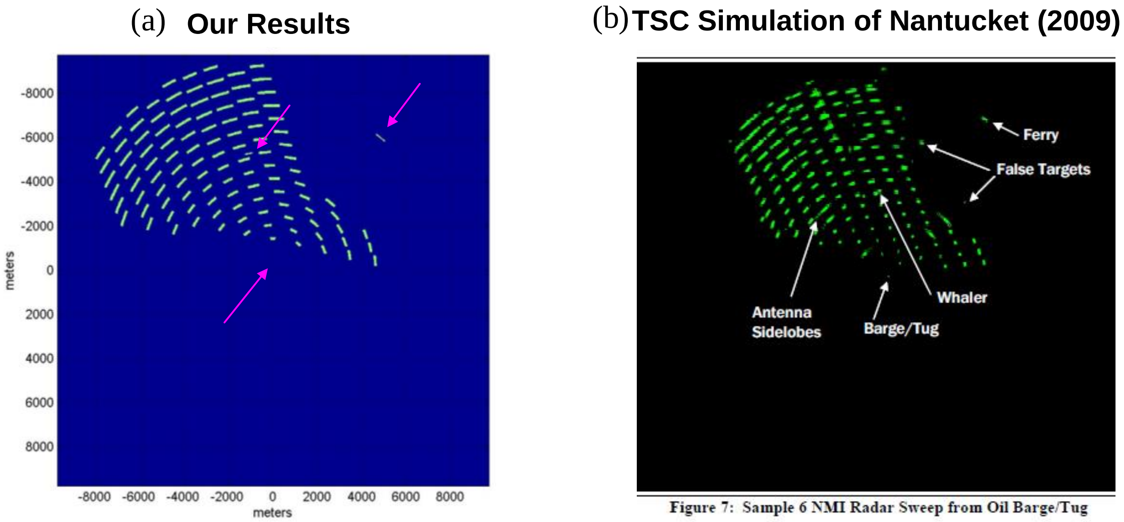
PPI Display

(Wind Turbine RCS = 30 dBsm,
Boat RCS = 25 dBsm @ 3GHz)

The red arrows marks the position of the two boats.

Fig. 11. Plots from the radar model tool. (a) Plot of the relative signal received. The two boats are shown by arrows. (b) The corresponding PPI display.

Fig. 11 shows the radar signal strength obtained from the radar model and the associated PPI display at S-band. The wind turbine nominal RCS is 30dBsm and the boat nominal RCS used in the modeling is 25 dBsm. The wind turbine RCS is comparable to the boat RCS. The two boats are shown using the red arrows among the wind farm. The wind farm is visible on the PPI display of the vessel radar operator. Boats can be detected and tracked outside the wind farm. However, the wind farm is a prominent target for the radar operator, and can make detection and tracking of boats more difficult within the farm.


(a) **Our Results**

(b) **TSC Simulation of Nantucket (2009)**

Figure 7: Sample 6 NMI Radar Sweep from Oil Barge/Tug

The arrows marks the position of the three boats.

Fig. 12. Comparison of PPI modeling results. (a) PPI display from radar model developed in this study, (b) PPI results from TSC Report [5]

Fig. 12 shows our results from the radar model developed in this study in comparison to the TSC results of Nantucket Sound [2]. Our results compare very well with their simulation. The TSC results show the primary scattering from the wind farm and boats that are clearly visible in both the simulations. TSC also shows some higher order mechanisms (e.g. multibounce between wind turbines and boat). These high order mechanisms were not considered in this study. Our results are also qualitatively comparable to those published by UK Kentish Flats measurement [7]. We did not have the complete wind farm configuration parameters to perform detailed modeling but a qualitative comparison shows that the modeling captures the key features in the PPI display. Interestingly the UK Kentish Flats measurements do not seem to show artifacts from multi-bounce mechanisms within the wind farm.

Fig. 13 shows a series of PPI snapshots as Boat 1 and Boat 2 traverse the farm in the paths shown earlier in Fig. 10. A total of 200 PPI snapshots were generated in the form of a movie for the dynamic scenario. The individual PPI displays are tagged by the frame numbers in Fig. 13. Animation of the movie shows that the boats could be seen on the PPI display and tracked by the marine radar, although Boat 2 was more difficult to discern when inside the farm.

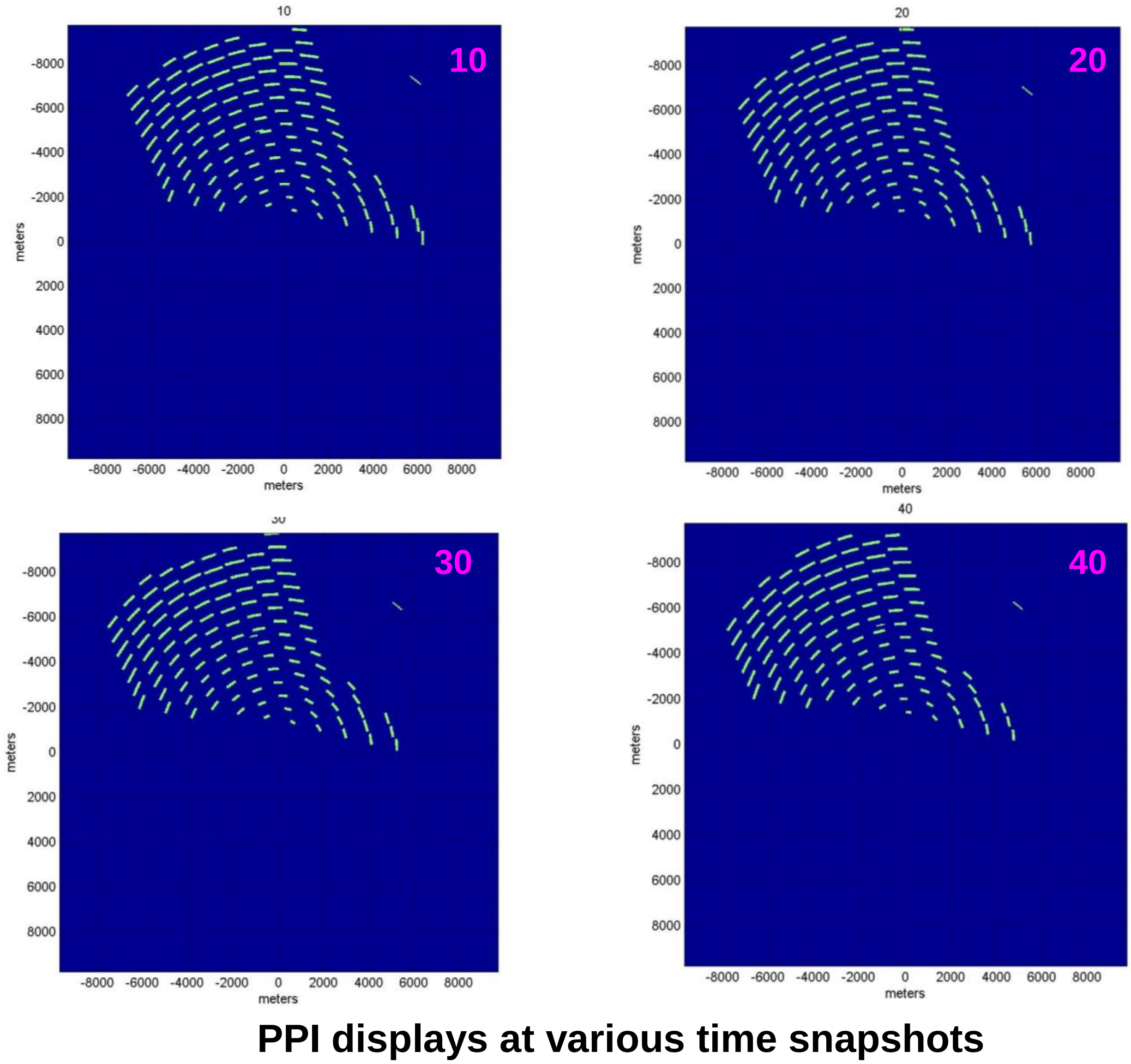


Fig. 13. PPI snapshots from the dynamic scenario. The PPI display are tagged by a frame number. There were 200 PPI snapshots that were generated for the dynamic encounter.

Next, we simulated a wind farm configuration provided by DOE. It consisted of a 10 x 10 wind farm spaced 1 km apart as shown in Fig. 14. The individual wind turbines were of the size specified in the NREL report [3]. Fig. 14 shows the scenario modeled. The dynamic scenario involved two boats moving in the vicinity of the wind farm. Boat 1 moves inside the farm and boat 2 starts inside the farm and finally exits the farms. The boat with the marine radar shown in red moves parallel to the wind farm and tracks the two boats. 200 PPI display time snapshots for the dynamic scenario were generated. Two example PPI snapshots are shown in Fig. 15 and Fig. 16 at S-band and X-band respectively.

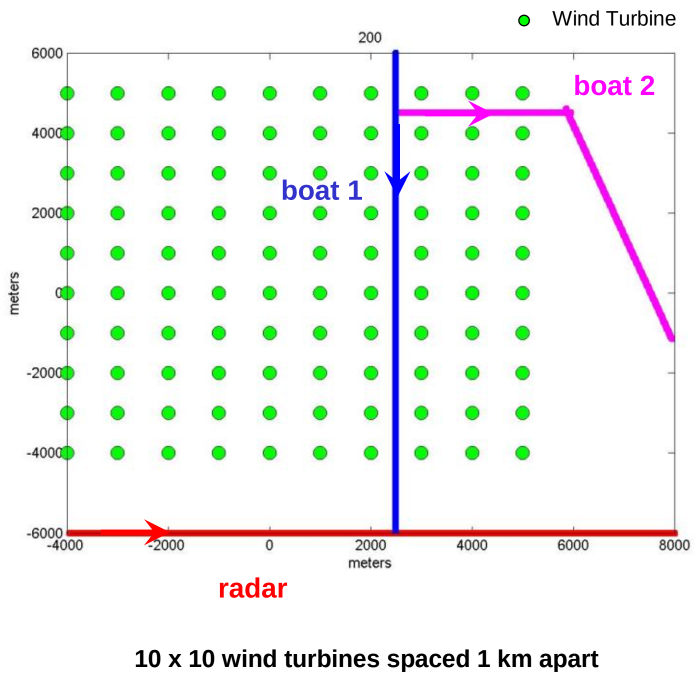


Fig. 14. Wind farm configuration used for simulations. The 100 NREL wind turbines were spaced 1 km apart. The radar and boat individual tracks are color coded.

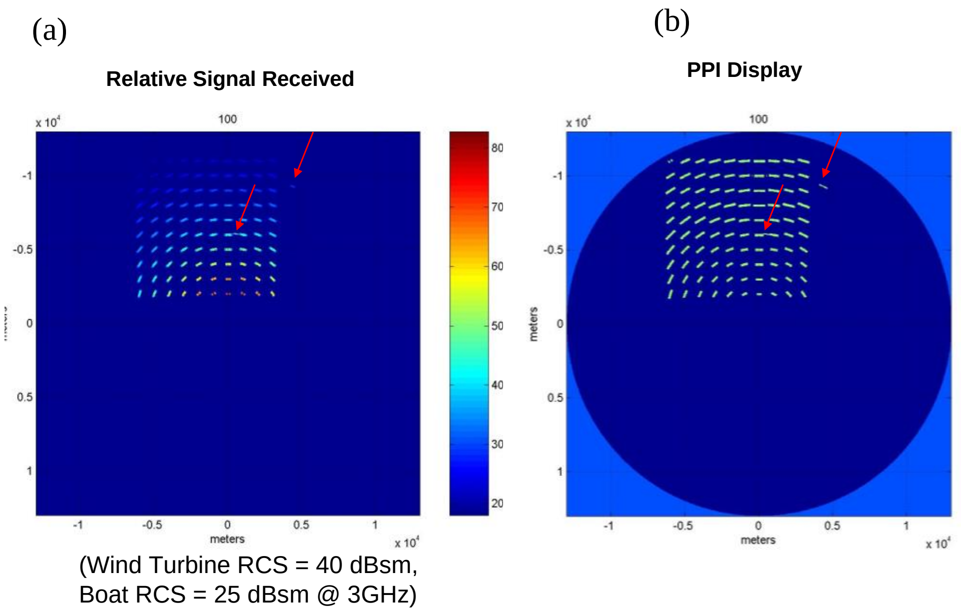
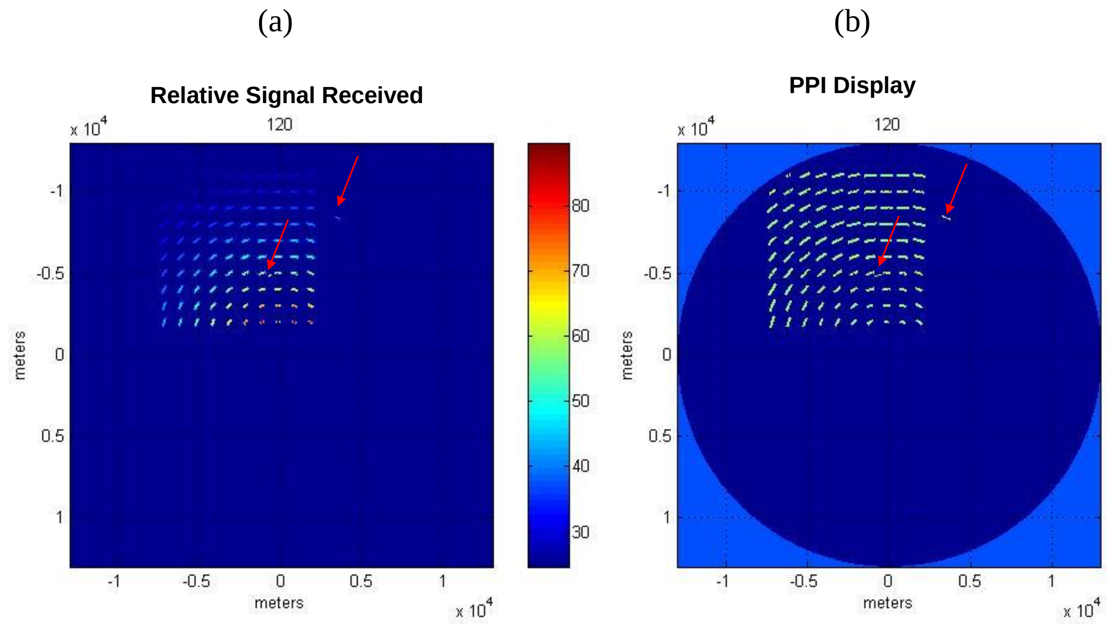


Fig. 15. Radar modeling and PPI simulation results at S-band. (a) Relative signal received. The nominal wind turbine RCS was 40 dBsm and nominal boat RCS was 25 dBsm. (b) PPI display shows the wind turbine and boat detections. The boat locations are marked by red arrows.

The PPI display for the wind farm is shown in Fig. 15. Fig. 15(a) shows the relative signal received from the radar model. The nominal wind turbine RCS was 40 dBsm and the nominal boat RCS was 25 dBsm. Fig. 15(b) shows the associated PPI display. The boat locations are marked by red arrows. The wind farm is visible on the PPI display of vessel radar operators. Boats can be detected and tracked outside the wind farm. However, the wind farm is a prominent target for the radar operator, and made detection and tracking of boats more difficult within the farm. Fig. 16 shows the results for the same wind farm configuration at X-band. The nominal wind turbine RCS was 45 dBsm and nominal boat RCS was 30 dBsm. The X-band results and conclusions are similar to the S-band results.



(Wind Turbine RCS = 45 dBsm,
Boat RCS = 30 dBsm @ 10GHz)

Fig. 16. Radar modeling and PPI simulation results at X-band. (a) Relative signal received. The nominal wind turbine RCS was 45 dBsm and nominal boat RCS was 30 dBsm. (b) PPI display shows the wind turbine and boat detections. The boat locations are marked by red arrows.

4. Assessment and Summary

For this case study we developed a radar model to simulate the dynamic scattering from wind farms. We used Xpatch and the EREPS model to simulate the RF scattering and propagation over ocean. We validated the Xpatch simulation using measurement data from the AFRL wind turbine collection. The validation showed reasonable comparison between Xpatch and measurements. In addition we validated the dynamic Doppler prediction capability by comparing to AFRL measured spectrograms. The Doppler predictions also showed reasonable comparison to the AFRL measurements. We simulated the corresponding PPI display as seen on marine radars. The study was performed for X-band and S-band. We simulated two scenarios that typical vessel operators would encounter while navigating within and around the wind farm.

The first scenario was that documented in the TSC report [5] for the Nantucket Sound offshore wind farm. Our PPI display simulations showed good comparison to those reported by TSC in [2]. The wind farm configuration in the second scenario was provided by DOE and was primarily used to draw the conclusions for this study. The PPI display showed that the wind farm is visible on the PPI display of vessel radar operators. Boats can be detected and tracked unobstructed outside the wind farm. However, the wind farm is a prominent target for the radar operator, and made detection and tracking of boats within the farm more difficult. Higher order effects were not considered in our PPI simulation and further study is needed to fully characterize their effects.

We can draw the following assessments from this study:

(1) Wind farm scattering would produce a confusing navigational picture when the boat being tracked is inside a wind farm.
(2) There would be minimal interference to tracking of vessels operating outside the wind farm. Though we did not study the case when the radar is inside the wind farm, this modeling approach can be extended to cover that scenario in future studies.
(3) This study agrees with the earlier Coast Guard determination on the Cape Wind project that "The Coast Guard assessment of impact on navigation safety falls within the moderate impact level.", [Page 12, [9]].
(4) Field measurements are needed to corroborate the modeling results. The next phase of DOE offshore wind projects may provide a good testing ground to collect marine radar data.

5. References

[1] M. Howard and C. Brown, "Results of the electromagnetic investigations and assessments of marine radar, communications and positioning systems undertaken at the North Hoyle wind farm," QinetiQ and the Maritime and Coastguard Agency, QINETIQ/03/00297/1.1, MCA Report MNA 53/10/366, Nov. 2004.

[2] D. Rugger, A. Pieramico and T. Koontz, "Report of the Effect on Radar Performance of the Proposed Cape Wind Project", Technical Report, TSC-CT113-53, Technology Services Corporation, December 16, 2008.

[3] K. C. Hill, G. Zelinski, T. Van, and C. Vogel, "Computational Electromagnetics (CEM) Prediction of a Windmill", 2007 Electromagnetics Code Consortium Annual Meeting, May 2007.

[4] J. Jonkman, S. Butterfield, W. Musial, and G. Scott, "Definition of a 5-MW Reference Wind Turbine for Offshore System Development", Technical Report, NREL/TP-500-38060, February 2009.

[5] Xpatch® Electromagnetic Simulation Software, Distributed by SAIC and AFRL, https://www.saic.com/products/software/xpatch, Jan 2012.

[6] H. Ling, R. Chou and S. W. Lee, "Shooting and bouncing rays: calculating the RCS of an arbitrarily shaped cavity", IEEE Trans. Antennas Propagat., vol. AP-37, pp. 194-205, February 1989.

[7] W. L. Patterson, C. P. Hattan, H. V. Hitney, R. A. Paulus, A. E. Barrios, Engineer's Refractive Effects Prediction System (EREPS), Naval Ocean Systems Center, 1990.

[8] Marico Marine, “Investigation of Technical and Operational Effects on Marine Radar Close to Kentish Flats Offshore Wind Farm Kentish Flats”, BWEA, April 2007.

[9] Coast Guard Memorandum, “Report of the Effects on Radar Performance of the Proposed Wind Farm Project and Advance copy of the USCG Findings and Mitigations”, 2009.

Appendix C1.2

Modeling Study on the Effect of Offshore Wind Farms on Airborne Radar

1. Scope of Study

DOD operates a number of airborne sensors. Some have high-resolution imaging capabilities, which depend on sophisticated processing algorithms such as Synthetic Aperture Radar (SAR), Inverse SAR (ISAR) and Ground Moving Target Indicator (GMTI).   This study was performed to model the effect of wind farms on radars installed on airborne platforms. Detailed information on these sensors is not available to us. The evaluation was performed for a generic class of radars operating in the X-Band under the SAR and GMTI modes.

2. Details of SAR Study

In this study we modeled the SAR and GMTI signatures of wind farms and evaluated their effect on the scene being acquired by an airborne sensor. The SAR formation process is shown in Fig. 1. The SAR formation requires an airborne sensor to collect frequency – aspect data. This data is post processed to form SAR images. SAR image formation uses frequency bandwidth to provide resolution in the down-range dimension, and the Doppler from the relative velocity of the scene with respect to the sensor to provide resolution in the cross-range dimension. For this algorithm to work properly, the scene is assumed to be stationary. Any movement in the scene will corrupt the Doppler estimates and cause artifacts in SAR images. This blade tip speed was 43m/s and at X-band provided a maximum blade Doppler of 2.8 kHz.

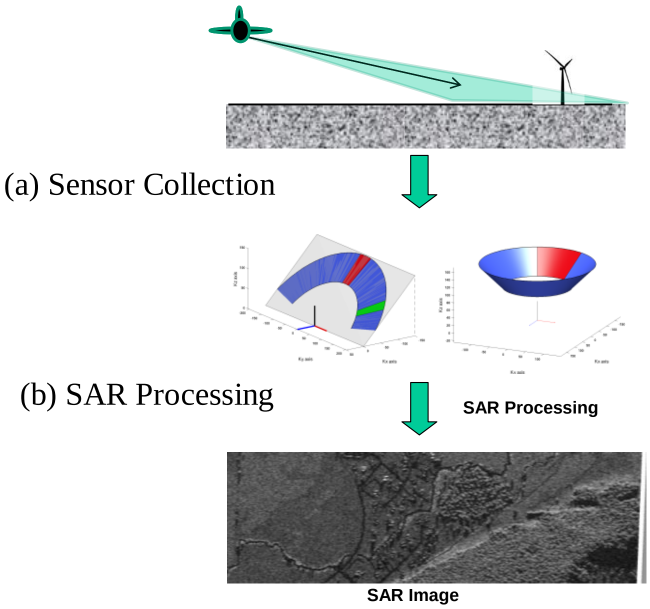


Fig.1. SAR Image formation and data collection process flow. (a) A side looking airborne sensor collects frequency – aspect data on the scene, (b) The data is post processed using sophisticated radar algorithms to form a SAR image.

For the study we built a 4x4 wind farm scene where the turbines are separated by 0.5km. The sensor and wind farm parameters are listed in Table 1. The 18MHz sensor bandwidth provides a range resolution of 8.3m. The wind turbines rotate at 12rpm which gives a maximum blade tip speed of 43m/sec. The maximum Doppler from the moving wind turbines at X-band is 2.8 kHz.

Sensor Parameters:
Frequency : 10 GHz
Resolution : 8.3m
Bandwidth : 18MHz
PRF : 3.26kHz
Radar Range: 20km
Aircraft Height : 3.5 km
EL,AZ : 10°,100°

Wind Turbine Parameters:
Number of turbines : 16
Turbine tip speed : 43m/s
Turbine Max Doppler : +/- 2.8kHz
Snapshots : 1024
Sampling: 0.0221°

Table 1. Sensor and wind turbine parameters chosen for the SAR simulation.

We added three boats in the scene. These boats were stationary. This is reasonable given the short imaging interval needed to form a SAR image. The wind turbine configuration is shown in Fig. 2. The boats are marked by magenta circles and the wind turbines are marked by green circles. The simulation was carried out using Xpatch as described in the associated marine radar study in Appendix C1.1. The CAD model used for the AFRL study shown in Fig 1 (a) of Appendix C1.1 was used in this study. The blade length in the CAD model is 34m, which is about half the size of the baseline 5-MW offshore wind turbine described in [3]. The blades are assumed to rotate at 12 rpm, leading to a blade tip speed of 43m/s. An RCS database at X-band for the wind turbine at the range of frequency and angles was simulated and stored. To simulate the dynamic scenario of the wind turbines spinning, 1024 snapshots of the blade positions were simulated using Xpatch. Once the database was computed for one turbine, the returns from all the wind turbines were combined coherently to form the total radar return from the wind farm. The electromagnetic simulation from the wind farm was post processed using a SAR post processing algorithm [1] to form a SAR image. An example SAR image of the stationary scene is shown in Fig. 2(b). The location of the boats in the SAR images is highlighted by the dashed circles. Since the wind turbines are stationary there are no artifacts generated from them in the SAR image. The boats can be clearly seen separately from the wind turbines.

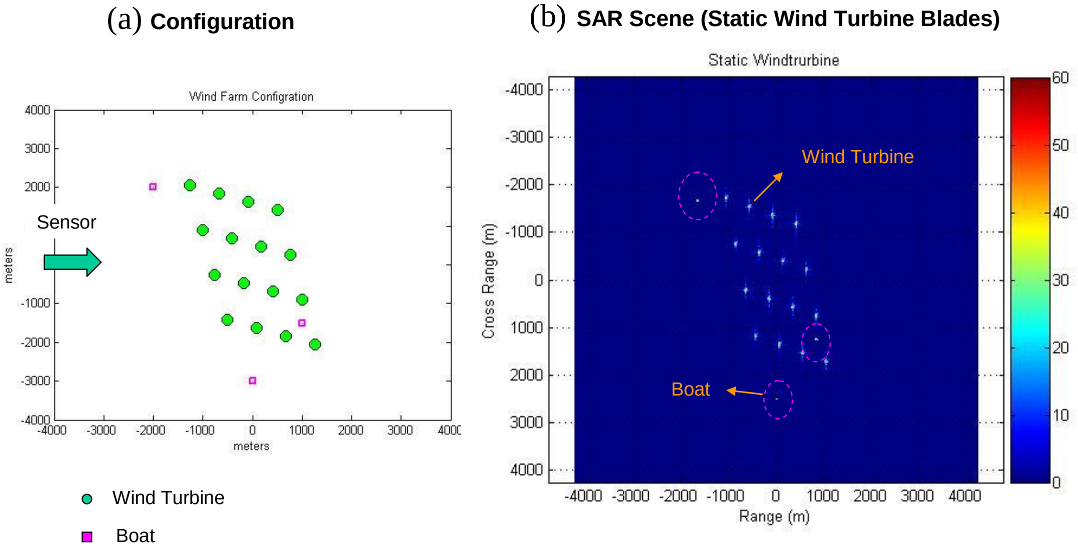
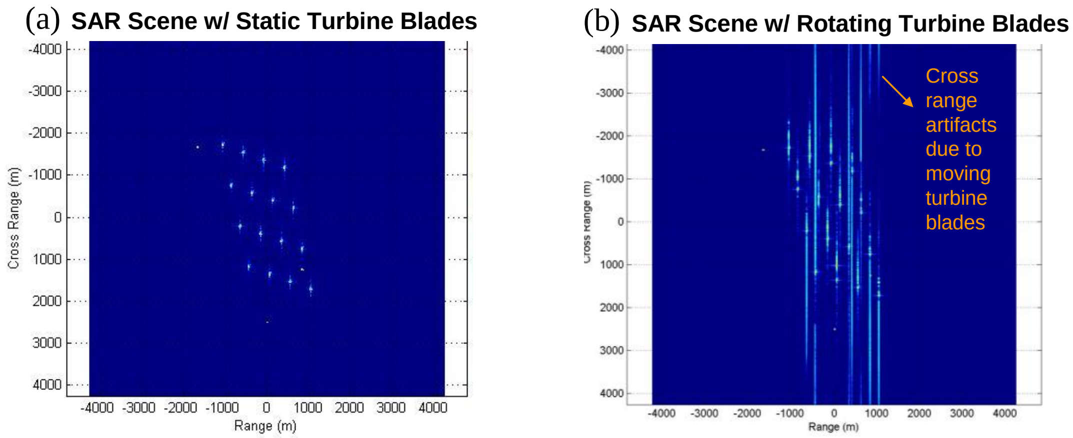

(a) **Configuration**
(b) **SAR Scene (Static Wind Turbine Blades)**

Fig. 2. (a) Wind farm configuration used in the study. The green circles denote the wind turbine location. The magenta circles denote the boat location. (b) The SAR image of the stationary scene. The boat SAR contributions are circled with dotted lines.

Next we generated the SAR image from a dynamic wind farm. The wind turbine returns from 1024 individual time snapshots for different turbine blade positions were Fourier processed to form the SAR image from a single wind turbine. The contributions from 16 wind turbines were similarly added up to form the SAR image from the complete wind farm. In addition the contribution of the 3 stationary boats was added to the RCS data. The RCS data was then post processed to form the SAR image from the dynamic wind farm. The SAR images from a stationary and a dynamic wind farm configuration are shown in Fig. 3. Moving blades generate Doppler features, which lead to cross-range artifacts in the SAR image of the scene. These artifacts run along the cross range dimension and can extend beyond the physical location of the wind farm in the SAR image.

We simulated 100 SAR image frames over an 8 sec time interval. Some of the SAR image frames are shown in Fig. 4. The artifacts change over the different time snapshots of the scene. The Doppler from the wind turbines blades depends on the position of the blades and as the wind turbines blades rotate these artifacts keep changing in amplitude and severity. The SAR image from any boat located within the cross-range location of the wind turbine would be affected since it would be quite difficult to discern the target from the rapidly changing wind turbine artifacts. In the example above there were three boats in the scene. The two boats in the scene in the same cross-range as the wind farm are affected by the artifacts. One of the affected boats is outside the wind farm. These artifacts can potentially interfere with target detection and recognition of boats in the vicinity of the wind farm. If we extrapolate the situation to the baseline 5-MW offshore wind turbine described in [3], which has a maximum blade tip speed of 80m/s, the Doppler aliasing in the resulting signatures would be even more severe.


(a) SAR Scene w/ Static Turbine Blades

(b) SAR Scene w/ Rotating Turbine Blades

Fig. 3. The SAR image from a stationary and dynamic wind farm configuration. (a) SAR image from stationary scene with static turbine blades. (b) SAR image from a dynamic scene with rotating turbine blades. The rotating blades cause cross-range artifacts in SAR image.

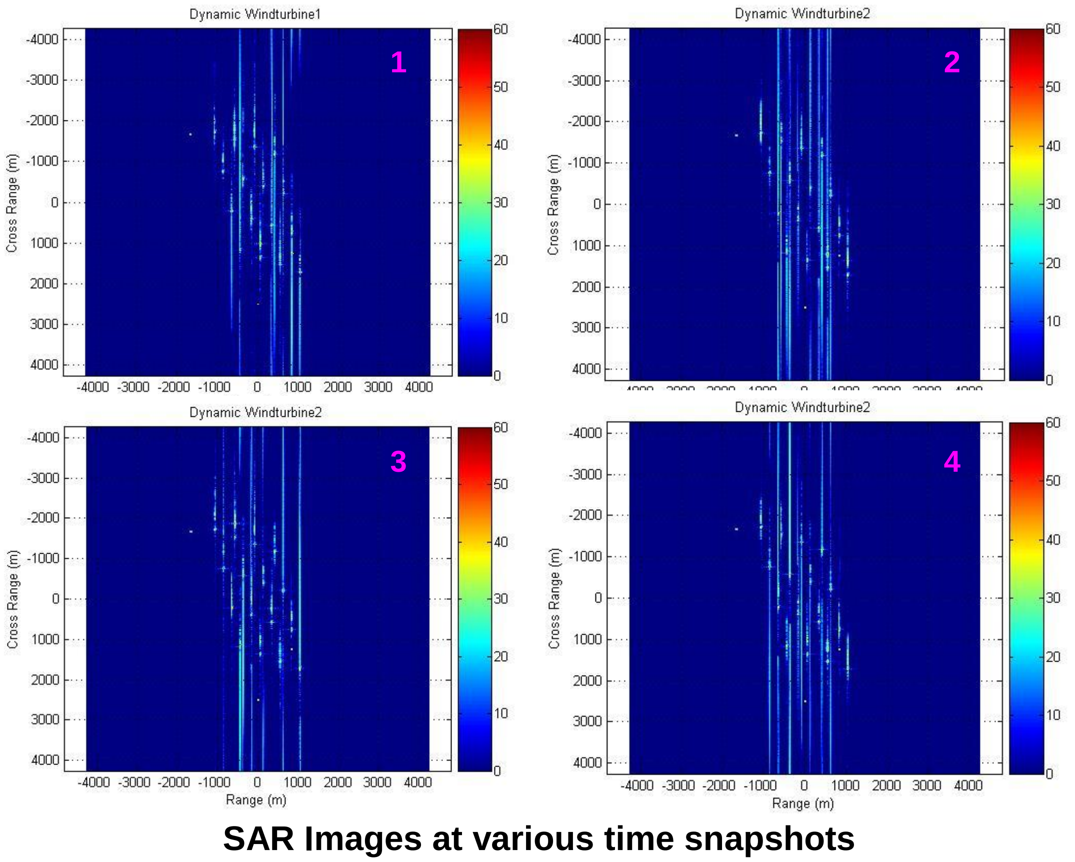
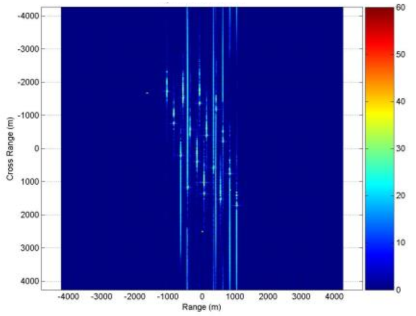


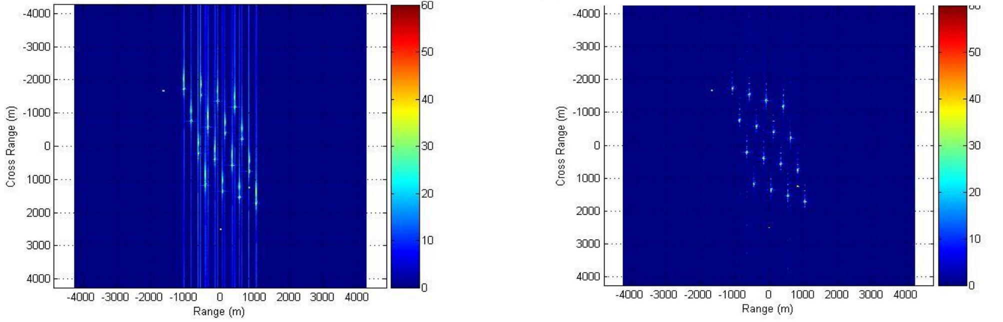
Fig. 4. SAR images at different time snapshots. The location and severity of the cross-range streaks keep changing. When an individual wind turbine blade is perpendicular to the radar LOS it causes the maximum corruption in the SAR image.

3. SAR Artifact Mitigation Study

We investigated two approaches to mitigate the artifacts due to wind turbine Doppler in SAR images. The first approach uses a simple averaging process. In this approach we take a number of successive SAR image snapshots of the scene and average them either coherently or incoherently to form an averaged SAR image. Fig. 5 shows the average SAR images from 16 views of the scene. The incoherent average SAR image which involves averaging the magnitude of the SAR image shows a 10 dB reduction in the amplitude of the artifacts. The coherent average SAR image involves the averaging the complex SAR image values from the 16 views. The coherent averaging shows much better performance and shows a 25dB reduction in the SAR image artifacts. Though the coherent SAR averaging processing gave better performance it is more difficult to acquire due to the need to maintain phase synchronization across multiple SAR frames.

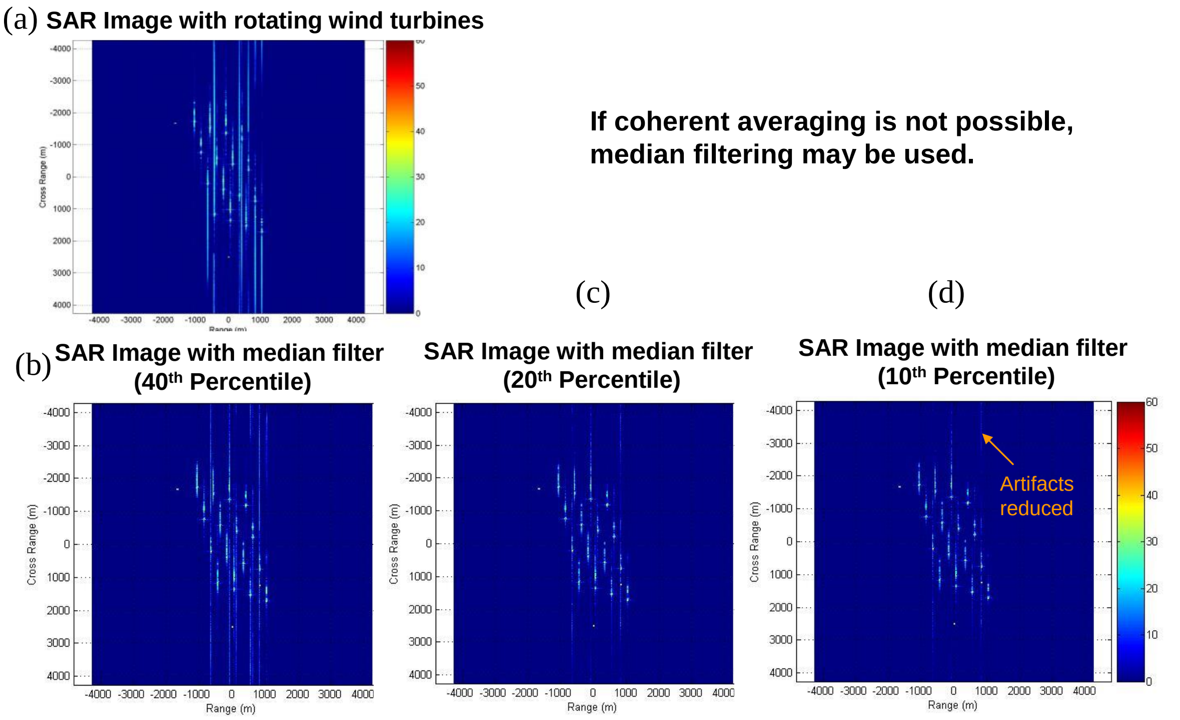

(a) **SAR Image with rotating wind turbines**

Averaging can be used to reduce the wind turbine artifacts in SAR images


(b) **SAR Image (Incoherent averaging of 16 views)**

(c) **SAR Image (Coherent averaging of 16 views)**

Fig.5. SAR artifact mitigation using averaging. (a) SAR image of dynamic scene with no mitigation, (b) SAR image of dynamic scene using incoherent averaging of 16 time snapshot SAR views, (c) SAR image of the dynamic scene using coherent averaging of 16 time snapshot SAR views.



(a) **SAR Image with rotating wind turbines**

If coherent averaging is not possible, median filtering may be used.

(b) **SAR Image with median filter (40th Percentile)**

(c) **SAR Image with median filter (20th Percentile)**

(d) **SAR Image with median filter (10th Percentile)**

Artifacts reduced

Fig. 6. SAR artifact mitigation using median filtering. (a) SAR image of dynamic scene with no mitigation. SAR image of dynamic scenes using median filter with different settings.(b) 40th percentile, (c) 20th percentile, (d) 10th percentile.

The artifacts change rapidly due to blade rotations. In the second approach, we use the transient nature of the artifacts to perform a median filter on a series of SAR image. Fig. 6 shows the median filter output from a series of 16 SAR images. Different median filters are tried with different percentile values. For example, to generate the 10th percentile median filter we take the time history of data in this case 16 frames. The 10th percentile is the value below which 10 percent of the pixel values may be found. For fast transients such as wind turbine artifacts, things change rapidly from frame to frame, a percentile filter provides good performance because the transients are only in a few frames whereas the stationary SAR features are in all the SAR frames. The choice of percentile is tunable depending on the how fast the artifacts are changing in the successive SAR frames. In our example the 10th percentile seemed to offer the best performance and resulted in a 20 dB reduction in SAR image artifacts. These approaches help mitigate the severity of the artifacts seen in SAR images of dynamic wind farms and can improve the performance of target detection and recognition algorithms.

4. Details of GMTI Study

We performed a similar study for a GMTI sensor. The GMTI sensor also uses Doppler processing to identify moving targets in the scene. The GMTI processing chain is shown in Fig. 7. A GMTI sensor collects the frequency – dell time data from a scene. The time history data are broken into individual CPI (coherent processing interval). The data are then Fourier transformed along the dwell time and frequency dimensions to generate a Range-Doppler chip. The Doppler estimate of the scene assumes targets moving in the scene with a linear velocity. The Doppler from the moving targets can be used to determine the speed and heading of the targets. The moving wind turbines in a wind farm introduce Doppler from the blades. This Doppler is due to the rotational motion of the wind turbine and not due to linear velocity of the target. Consequently, the wind farm induced Doppler shows up as artifacts in the GMTI chip.

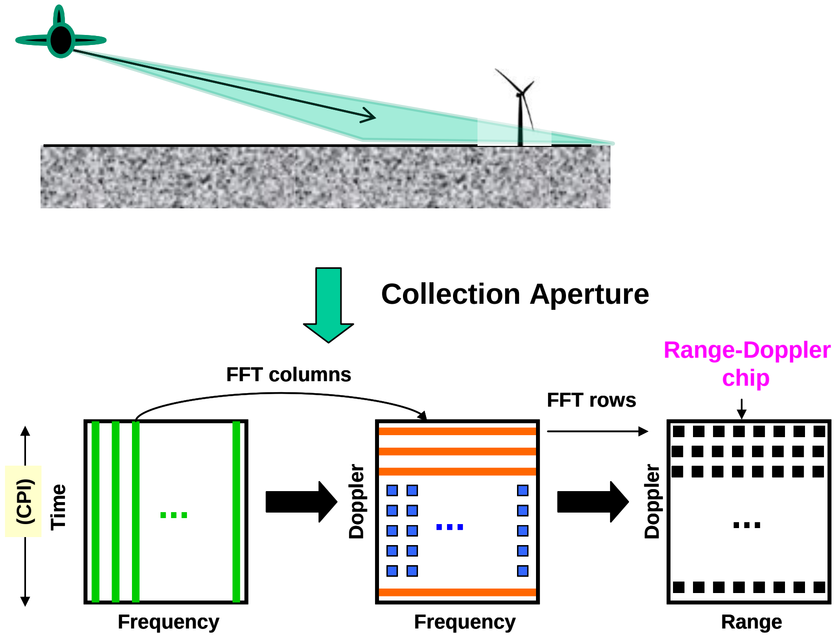


Fig. 7. GMTI range Doppler chip formation and data collection process flow. (a) A side looking airborne sensor collects time history data of the scene, (b) The data is post processed using Fast Fourier Transforms (FFT) to form a range Doppler chip.

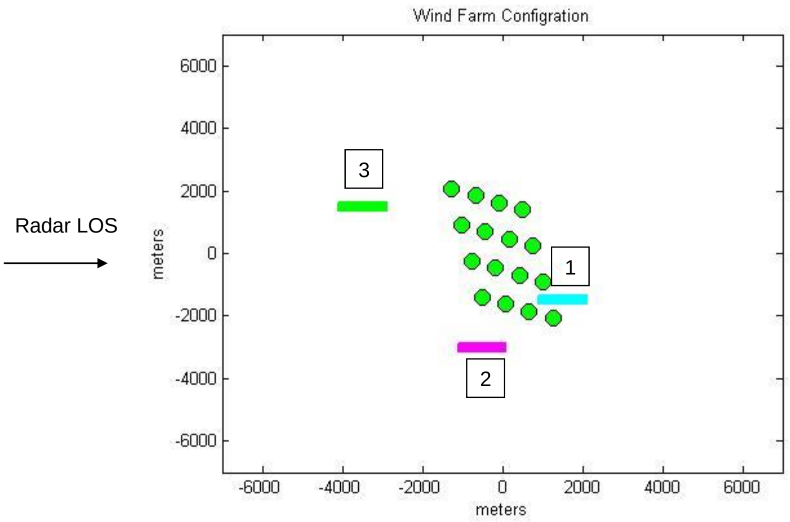
For the study we built a 4x4 wind farm scene with turbines separated by 0.5km. This wind farm model is identical to that used in the SAR study. The sensor and wind farm parameters are listed in Table 2. The wind turbine blades are assumed to rotate at 15rpm, which gives a maximum blade tip speed of 53m/s. This blade tip speed at X-band provided a maximum blade Doppler of 3.5 kHz. The radar bandwidth is 3.75MHz at 10 GHz providing a range resolution of 40m.

Sensor Parameters:
Frequency : 10 GHz
Resolution : 40m
Bandwidth : 3.75MHz
PRF : 18kHz
EL,AZ : 10^{o},70^{o}

Wind Turbine Parameters:
Number of turbines : 16
Turbine tip speed : 53m/s
Turbine Max Doppler : +/- 3.5kHz

Table 2. Sensor and wind turbine parameters chosen for the GMTI simulation.

Three boats are present in the simulated scene. The wind farm configuration and the boats are shown in Fig. 8. The three boats were assigned three different speeds 6.67km/hr, 13.34 km/hr and 20km/hr. These speeds provide a Doppler at X-band of 123.5Hz, 257 Hz and 370.5 Hz, respectively.



The three boats are moving at 6.67 km/hr (123.5 Hz), 13.34 km/hr (247 Hz), 20 km/hr (370.5 Hz)

Fig. 8. Wind farm configuration. There are three boats in the scene that are moving.

Fig. 9 shows the GMTI range-Doppler chip of a scene with stationary wind turbines and moving boats. The stationary wind turbines give zero Doppler and hence are clustered along the zero Doppler line in the middle of the range Doppler chip. The three boats can be resolved in the range-Doppler chip due to their motion and are clearly visible and marked by arrows in the chip.

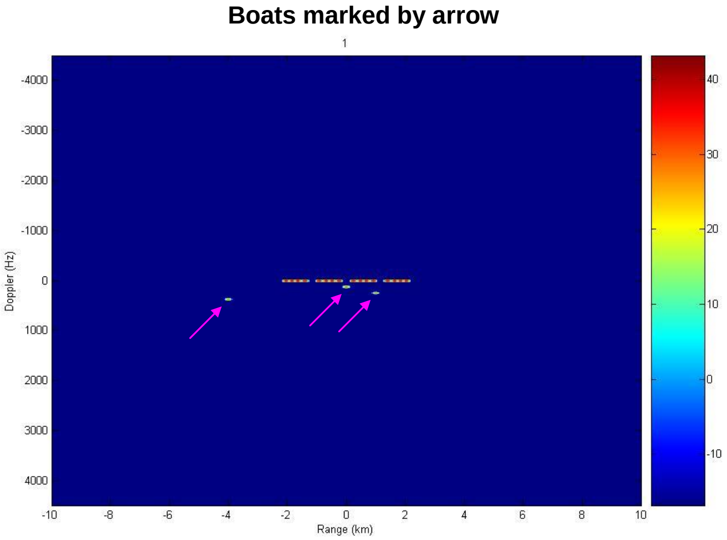


Fig. 9. GMTI range Doppler chip of the scene with stationary wind turbine blades. The three moving boats are marked by arrows on the chip.

Fig. 10 shows the range Doppler chip of the scene with the wind turbines rotating. The Doppler from the individual wind turbine blades cause Doppler streaks in the chip. These artifacts are Doppler flashes which become visible when the radar line of sight is perpendicular to the blade position.

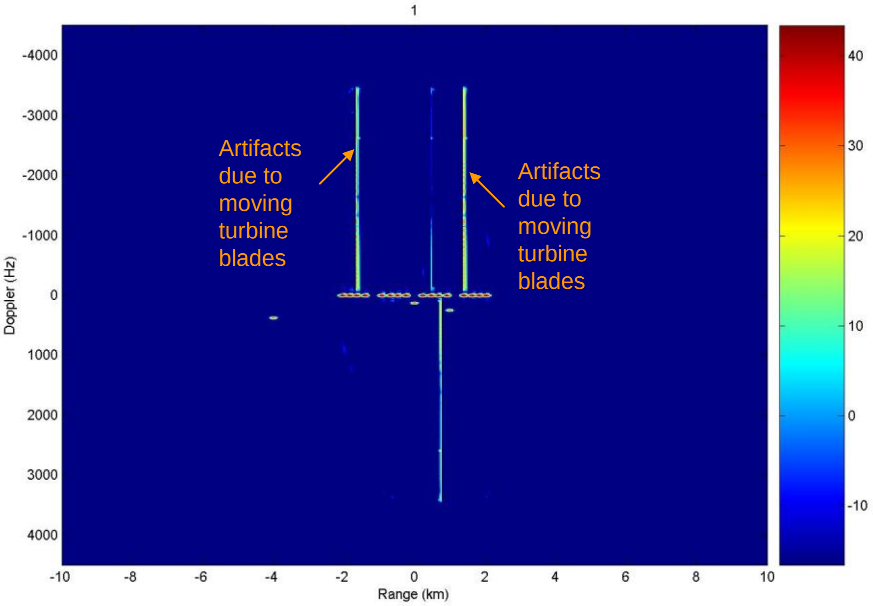


Fig. 10. GMTI range Doppler chip of the scene with moving wind turbine blades. The artifacts due to moving blades show up as Doppler streaks in the chip.

The artifacts extend in both the positive and negative Doppler axis depending on whether the blades are moving towards or away from the sensor. Since the blades move much faster than the boat in the scene, the rapidly changing artifacts will interfere and corrupt all boat responses which are in the same range cells as the wind turbine.

Fig. 11 shows the range-Doppler chips generated at successive time snapshots. The three boat responses can be seen in the range-Doppler chips. In addition the Doppler artifacts due to the fast moving blades can be seen. These artifacts change rapidly in the different snapshots due to the changing positions of the wind turbine blades as they rotate. These artifacts can interfere with the ability of target detection and recognition algorithms.

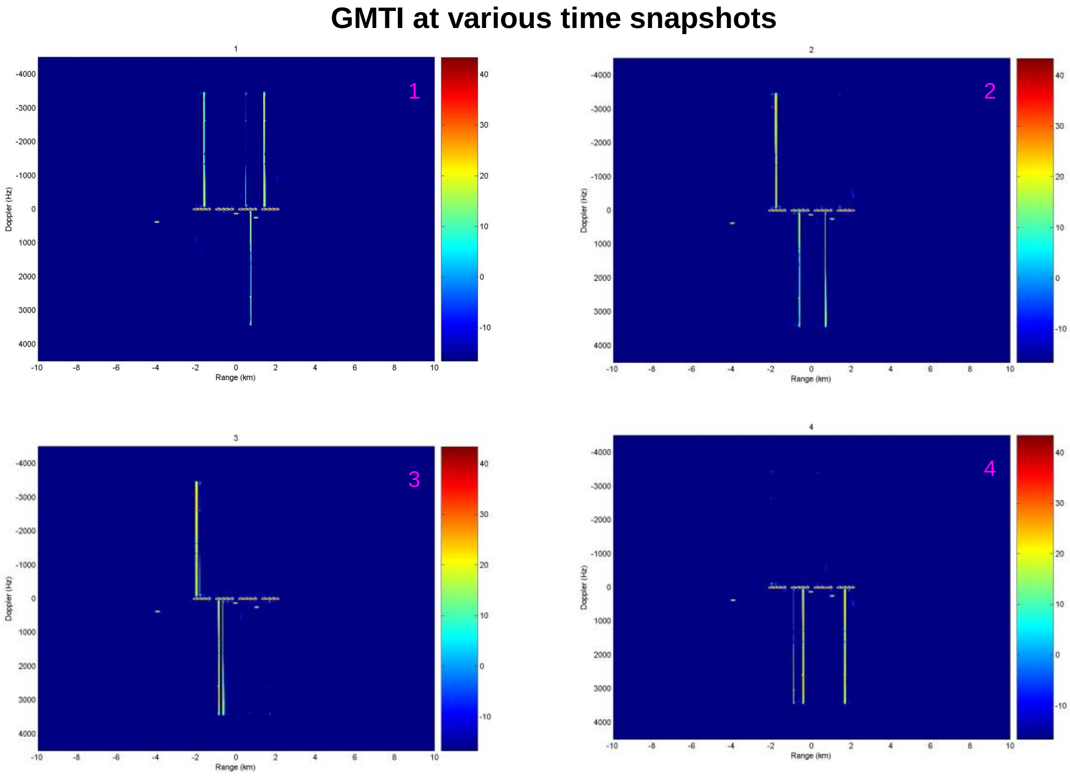
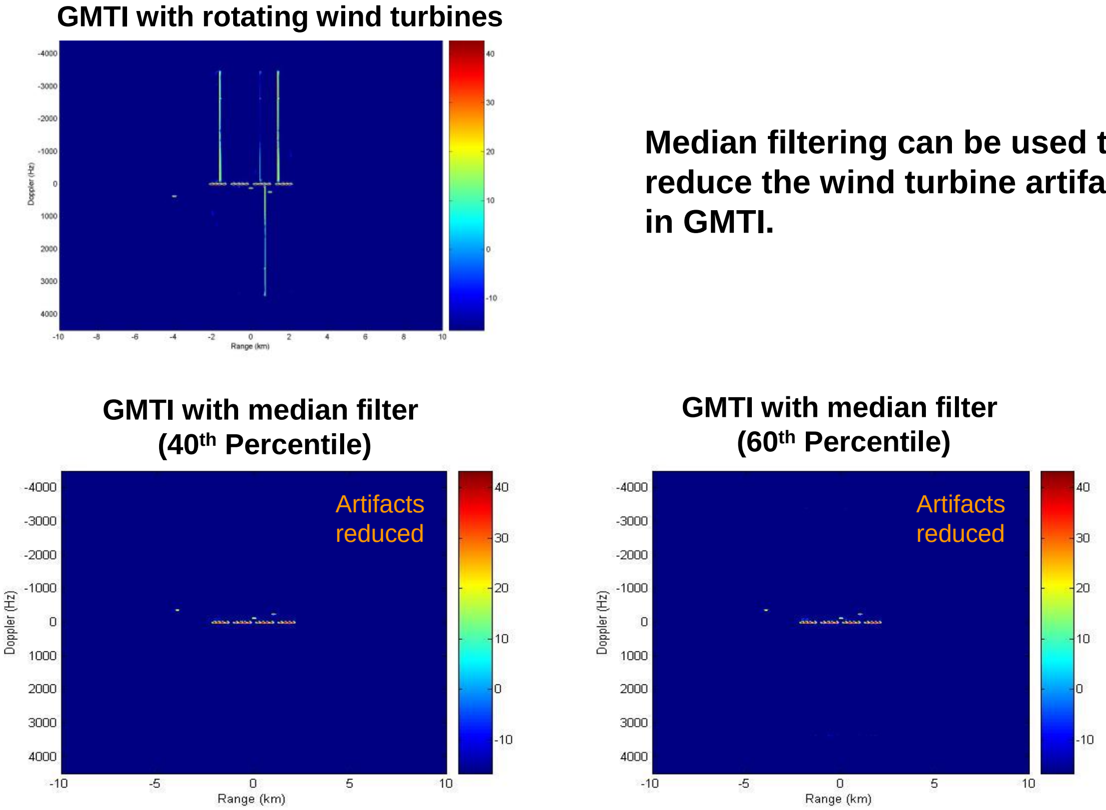

GMTI at various time snapshots

Fig. 11. GMTI range Doppler chip of the scene with moving wind turbine blades at different time snapshots. The artifacts due to moving blades change at different time snapshots due to different location of blades in the individual wind turbines.

5. GMTI Artifact Mitigation Study

We investigated a mitigation approach for the Doppler artifacts in GMTI. We adopted the median filter used in the SAR study to access it performance for the GMTI sensor. The artifacts are rapidly changing due to blade rotations. We can use the transient nature of the artifacts to perform a median filter on a series of GMTI range Doppler chips. Fig. 12 shows the median filter output from a series of 16 GMTI range Doppler chips. The different median filters are chosen using different percentile values. The 40th percentile is the value below which 40 percent of the pixel values may be found in the time history of the GMTI range Doppler frames. The artifacts change frame to frame, a percentile filter filters out the transients whereas and keeps the stationary SAR features which are are in all the SAR frames. The choice of percentile is tunable depending on the how fast the artifacts are changing in the successive SAR frames. In our example the 60th percentile seemed to offer the best performance and offered a 35 dB reduction in artifacts in range Doppler chips.



Median filtering can be used to reduce the wind turbine artifacts in GMTI.

Fig.12. GMTI artifact mitigation using median filtering. (a) Range Doppler chip with no filtering, (b) Range Doppler chip using 40th percentile median filter, (c) Range Doppler chip with 60th percentile median filter.

6. Assessment and Summary

For this case study we developed a radar model to simulate the dynamic scattering from offshore wind farms for the types of sensors (SAR and GMTI) that typical airborne platforms would operate in coastal waters. We developed a SAR and GMTI modeling capability using Xpatch data. The study was performed for X-band sensors. We simulated one scenario that typical airborne sensors would encounter while carrying out surveillance around a wind farm. The 4 x 4 wind farm simulations were used to draw the conclusions for this study. The SAR simulations showed that the dynamic wind farm will cause cross range artifacts in SAR images. These artifacts extend along the cross-range dimension and can be seen beyond the physical location of the wind farm in the SAR image. These artifacts will corrupt the SAR image and the extent of corruption is dependent on the sensor parameters. The GMTI simulations showed that the dynamic wind farm will cause Doppler artifacts in range Doppler chips. The corruption in range Doppler chips is limited to the Doppler extent of the turbine blades, and is bursty in time. These artifacts can potentially interfere with tracking of boats in coastal waters. The GMTI and SAR image simulation show that the wind farm is visible in SAR and GMTI signatures. Doppler from rotating blades can cause artifacts in SAR and GMTI signatures and could potentially result in interference with identification and tracking of boats. Higher order effects were not considered in the simulation and further study is needed to fully characterize their effects. Lastly, the size of the turbines considered in the study is about half of the baseline 5-MW offshore wind turbine described in [3]. Therefore, the severity of the artifacts is expected to be even worse for the latter. However, this would not the change the conclusions arrived in this study.

We can draw the following assessments from this study,

(1) Wind farm scattering will produce artifacts in SAR and GMTI signatures generated by airborne sensors when a wind farm falls within the coverage area of the radar beam. This could potentially impact the performance of identification and tracking algorithms.
(2) We did not examine higher order effects such as multiple scattering and interaction with ocean surface. Further study is needed to fully characterize their effects [4].
(3) Signal processing of the signatures may be a viable approach to mitigate the effect of dynamic wind turbines. Assuming these mitigation factors are studied and implemented, the impact on recognition and tracking could be reduced to within the moderate level.

7. Reference

[1] Roger J. Sullivan, Microwave Radar: Imaging and Advanced Processing, Artech House, 2000.

[2] R.Bhalla and H. Ling, “Report on Effects of Wind Farms on Marine Radar Performance”, Appendix C.1.1.

[3] J. Jonkman, S. Butterfield, W. Musial, and G. Scott, “Definition of a 5-MW Reference Wind Turbine for Offshore System Development”, Technical Report, NREL/TP-500-38060, February 2009.

[4] A. Naqvi, N. Whitelonis and H. Ling, “Doppler features from wind turbine scattering in the presence of ground,” *Progress in Electromag. Research Lett.*, vol. 35, pp. 1-10, 2012.

Appendix C1.3

Modeling Study on the Effect of Offshore Wind Farms on HF Radar

1. Scope of Study

A network of HF radar sensors is operated by the National Ocean and Atmospheric Administration (NOAA) for large-area ocean surface current monitoring out to 250km off the US coast. They operate in the 4 to 50 MHz frequency range. There are about 130 HF radars in the network, where a majority of them are CODAR (Coastal Ocean Dynamics Applications Radar) systems made by CODAR Ocean Sensor Limited. Of the other 14 non-CODAR systems, 9 are WERA (Wave Radar) systems developed in Germany. The data from these ocean sensors are used by a number of federal, state and local agencies for search and rescue, water quality monitoring, rip current prediction, marine navigation, fisheries and ecosystem management, and oil spill response. Although these HF radars are land based, they look exclusively into the ocean and are therefore included in our present study.

These radars use an FMCW waveform for ranging, and use Doppler processing to extract the ocean wave and current information. In addition, direction finding or beamforming techniques are used to acquire azimuth bearing information. Since these sensors must look through any obstructions between the coastline and the ocean by propagating a vertically polarized electromagnetic wave along the ocean surface, offshore wind farm structures may pose a serious concern. Two notable studies have been done to examine the effect of offshore wind farms on these HF sensors. In [1], L. Wyatt and her collaborators presented measured data on a WERA system at 13MHz from the Rhyl-Flats wind farm in UK's Liverpool Bay. Fig. 1 shows the data from before and after the operation of the farm, which clearly shows the effect of the wind farm in raising the background clutter versus the ocean Doppler return. More recently, C. A. Teague

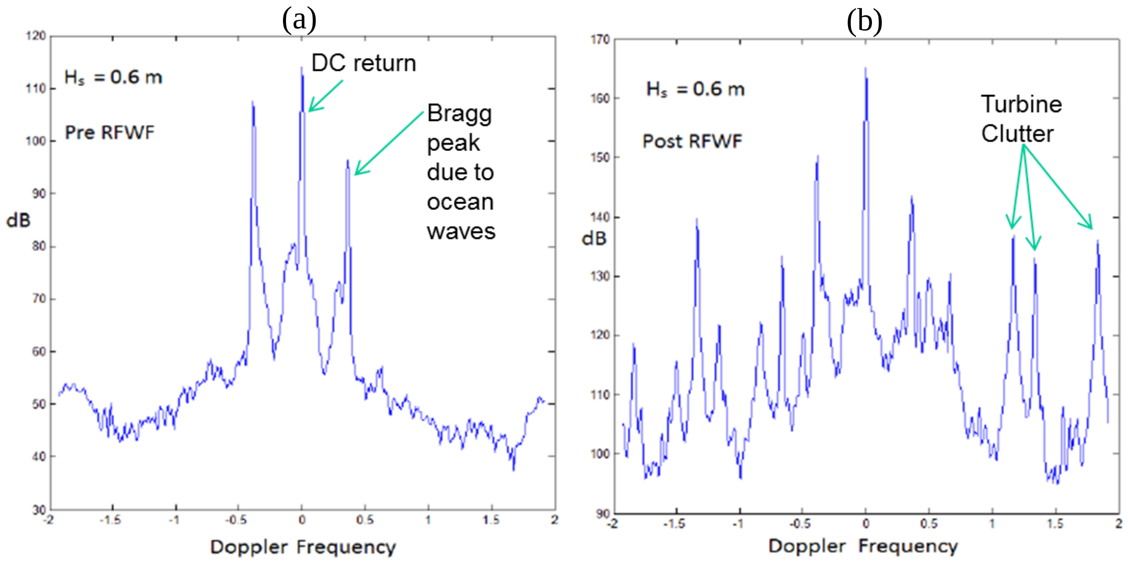


Fig. 1. Measured Doppler spectra from a WERA HF radar. (a) shows before and (b) shows after the operation of the Rhyl-Flats wind farm in the UK (from [1]).

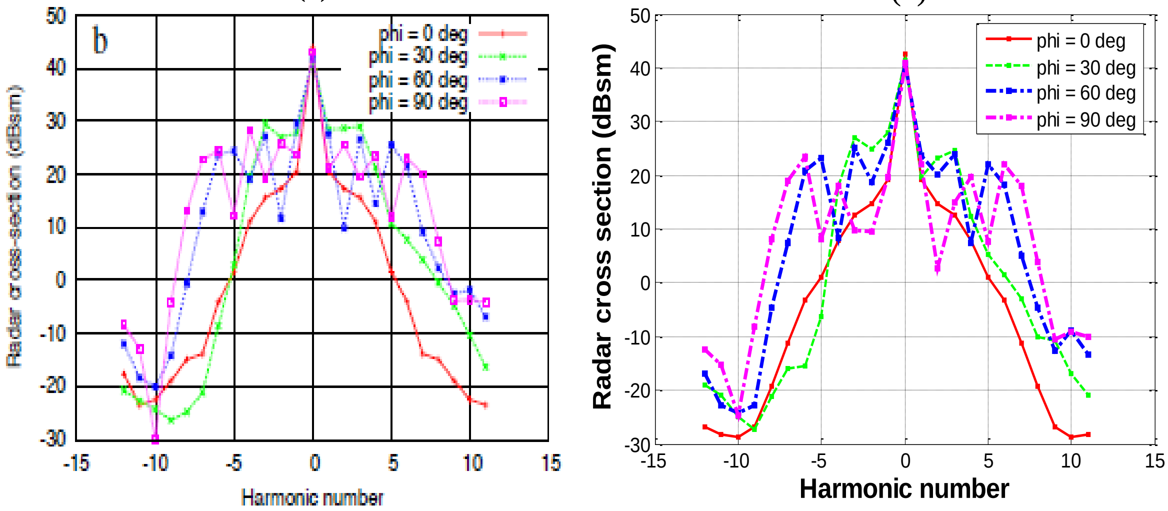
and D. Barrick of CODAR Ocean Sensors Ltd. carried out a simulation study [2], in which electromagnetic modeling using the Numerical Electromagnetics Code (NEC) was conducted to predict the level of Doppler clutter generated by a typical wind turbine.

In this study, we examine the radar backscattering clutter and forward electromagnetic shadow generated by a typical wind farm in the HF frequency range using computational electromagnetic simulation. This report is organized as follows. In Sec. 2, we present results of our simulation using nominal offshore wind farm parameters in [4]. In Sec. 3, some detailed issues with numerical modeling are discussed. Our summary and assessment are presented in Sec. 4.

2. Modeling Methodology and Simulation Results

Even though offshore wind turbines are physically large, their sizes are only on the order of a few wavelengths at HF frequencies. Consequently, Xpatch, which is based on high-frequency ray tracing and was employed in Appendices C1.1 and C1.2, would not be applicable in the HF frequency range. Moreover, the scattering phenomenology between HF waves and wind turbines may be quite different from that at higher frequencies. Therefore, we must resort to full-wave modeling, i.e., rigorous numerical solution to Maxwell's equations, while carrying out the electromagnetic simulation.

We apply FEKO [3], a commercially available electromagnetic solver, to model dynamic wind farm clutter. The method of moments solver is used to arrive at a full-wave solution. The wind turbine is modeled approximately by thin wires, similar to the earlier study in [2] using NEC. Fig. 2 shows the comparison between the Doppler spectra from [2] and our simulation. The agreement is good. This gives us confidence in simulating more complex geometries.



(a) (b)

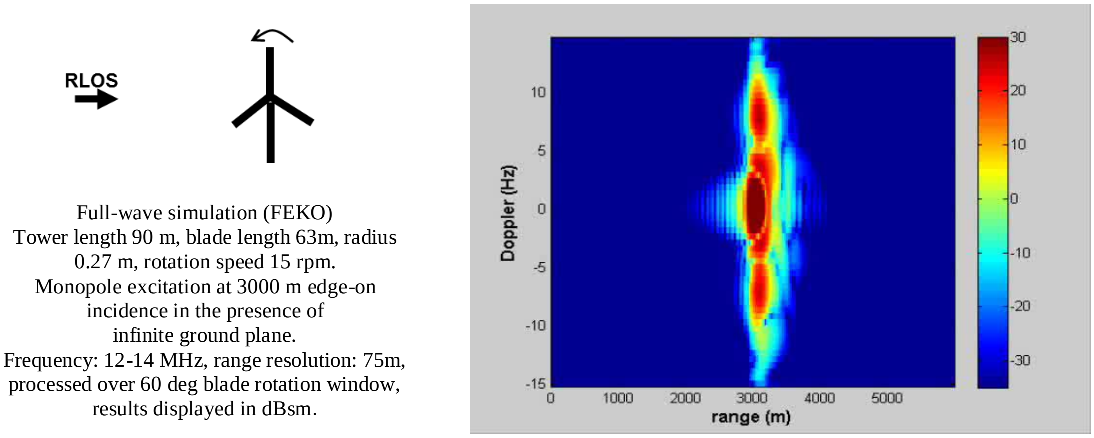
Fig. 2. Simulated Doppler spectra using thin-wire modeling with the following parameters: tower height=60m, blade length=42m, rotation rate=15rpm, radar frequency=13.5MHz. (a) Results from [2] using the Numerical Electromagnetics Code (NEC). (b) Our simulation.

For our study, the following parameters are used: tower height=90m, blade length=63m, rotation speed=15rpm. The dimensions correspond to the nominal dimensions of a baseline 5-MW offshore wind turbine described in [4], while the rotation rate exceeds the 12.1rpm maximum rotation rate given in [4]. As a result, the amount of Doppler shift reported in this study is exaggerated by about 24%. The turbine is assumed to be perfectly conducting. This assumption will likely lead to results that overestimate the scattering contribution from the wind farm. An infinite ground plane is assumed to model the water surface, which is highly reflecting at HF frequencies. For the HF radar, we assume the antenna is a monopole located at 3000m from the center of the wind farm, and the transmitted wave is incident at edge-on relative to the rotation plane of the turbine blades. The frequency bandwidth is assumed to be 12-14MHz, leading to a radar range resolution of 75m. The wire radius in the thin-wire model is assumed to be 0.27m, which is the maximum allowable under the thin-wire approximation (1/80 of a wavelength at 14MHz). The effect of the thin wire model and the wire radius will be discussed later in Sec. 3.

2.1 Wind Farm Clutter Response

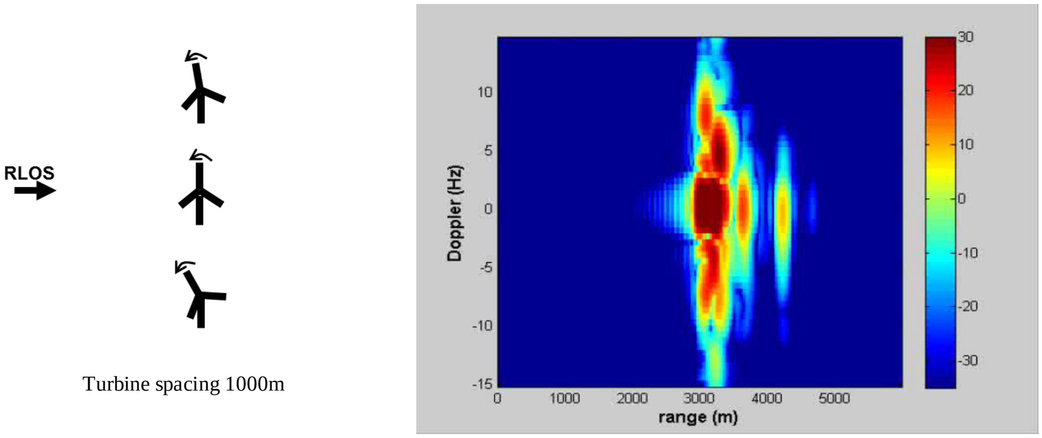
To properly simulate the range-Doppler response of the scattering from a turbine, electromagnetic simulation is performed over multiple time snapshots of the turbine structure. This is carried out by articulating the blade orientation of the CAD model and carrying out EM simulation at each snapshot in 3-degree steps. The sampling is chosen to provide a non-aliased Doppler response of the blade. The complex radar cross section (RCS) data are collected over multiple frequencies and for multiple snapshots. They are then 2-D Fourier transformed to generate a range-Doppler plot. The processing window in dwell time is chosen to cover a 60° blade rotation window to create a series of "instantaneous" range-Doppler plots. Fig. 3 shows one frame of the range-Doppler plot. The RCS strength is indicated by color on a dBsm scale. It can be observed that the turbine return is localized in range to around the 3km range bin. There is no significant ringing in range, even though the blade and tower lengths are only a few wavelengths and subject to resonant scattering phenomena. The Doppler response contains a spread of +-9Hz, which is the maximum Doppler shift due to the rotating blade tips. A strong DC is observed at zero Doppler. This is due to the time-invariant tower return. When the entire sequence of range-Doppler plots is viewed as a movie, the blade flashes can be vaguely seen, although they are not as prominent as those observed at microwave frequencies (see Appendices C1.1 and C1.2). Furthermore, due to the presence of the conducting ground plane, there are some interactions between the turbine and the ground that complicate the return. Nonetheless, we conclude from this data that wind turbine clutter is localized in range and spreads in Doppler to +-9Hz.

Next, the simulation is expanded to multiple turbines. Fig. 4 shows the case of a 3x1 turbine layout, where the turbines are lined up at approximately the same range from the radar. The turbine spacing is 1000m. In the dynamic simulation, the turbines have the same rotation rate, but the starting angles are set 20 deg apart from each other. It can be seen that the direct return from the individual turbines are overlapped in range. Some additional range-delayed returns can also be observed. They are due to multiple scattering between the turbines. However, the strengths of these higher order interactions are quite weak. Also, their Doppler spreads are more confined, indicating that that they are predominately from the stationary towers. Fig. 5 shows



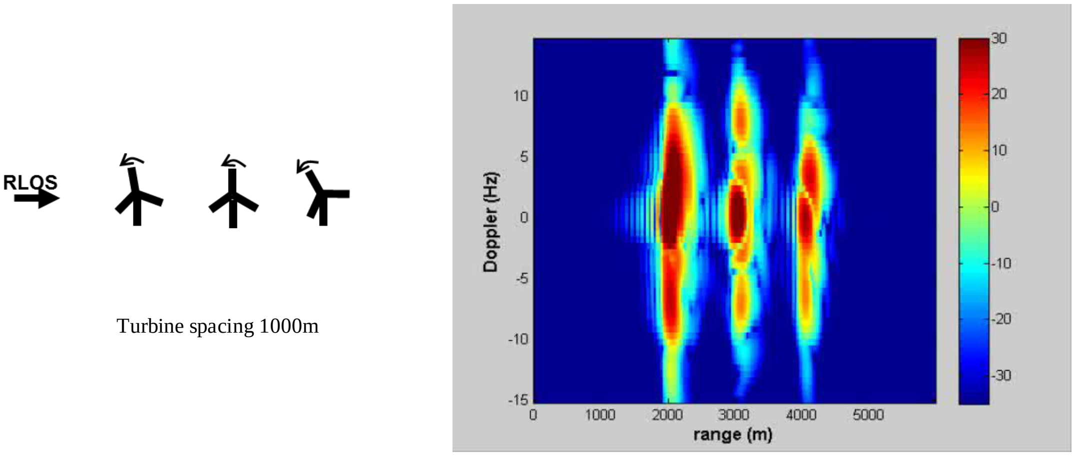
Full-wave simulation (FEKO)
Tower length 90 m, blade length 63m, radius
0.27 m, rotation speed 15 rpm.
Monopole excitation at 3000 m edge-on
incidence in the presence of
infinite ground plane.
Frequency: 12-14 MHz, range resolution: 75m,
processed over 60 deg blade rotation window,
results displayed in dBsm.

Fig. 3. Range-Doppler plot of the radar clutter from one single wind turbine.



Turbine spacing 1000m

Fig. 4. Range-Doppler plot of the radar clutter from a 3x1 wind farm.



Turbine spacing 1000m

Fig. 5. Range-Doppler plot of the radar clutter from a 1x3 wind farm.

the case of a 1x3 turbine layout, with the same 1000m inter-turbine spacing. In this case, the distinct returns from the three turbines can be easily seen, as they are separated in range by 1000m. Interestingly, we do not seen any significant shadowing of the second and third turbines due to the first turbine. Furthermore, no range-delayed returns of to multiple scattering between turbines are noticed. Fig. 6 shows the case of a 3x3 turbine layout with the radar line of sight (RLOS) at the left. In this case, the returns from each column of turbines are clustered in range. The slight separation in range is due to the finite distance difference from the radar. Again, there is no significant showing of the second and third columns from the first column of turbines. Some range-delayed scattering returns are observed, which are probably due to inter-column multiple scattering. Fig. 7 shows the same turbine farm setup, but the radar is moved by 45 deg to an oblique incidence from edge-on to the turbine rotation plane. In this case, six prominent range returns are seen. Furthermore, the maximum Doppler spread of each return is reduced by approximately a cosine(45°) factor, due to the reduction in the radial velocity of the blades with

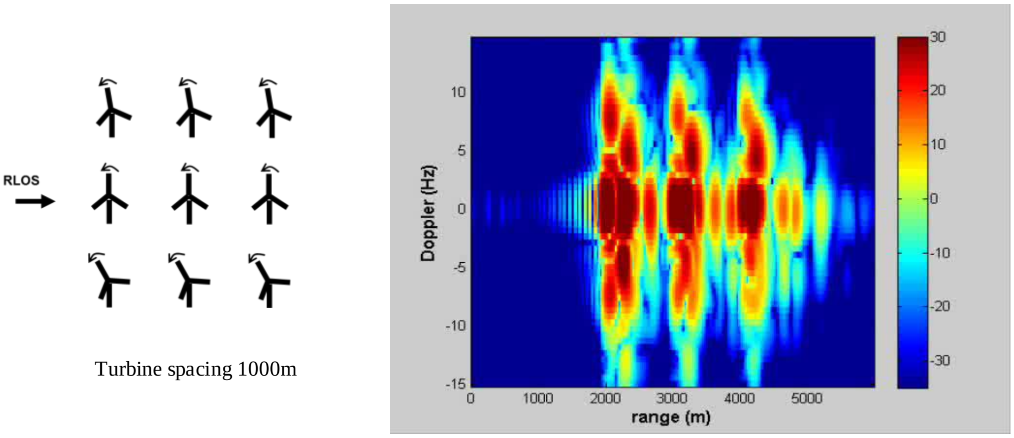


Fig. 6. Range-Doppler plot of the radar clutter from a 3x3 wind farm at edge-on incidence.

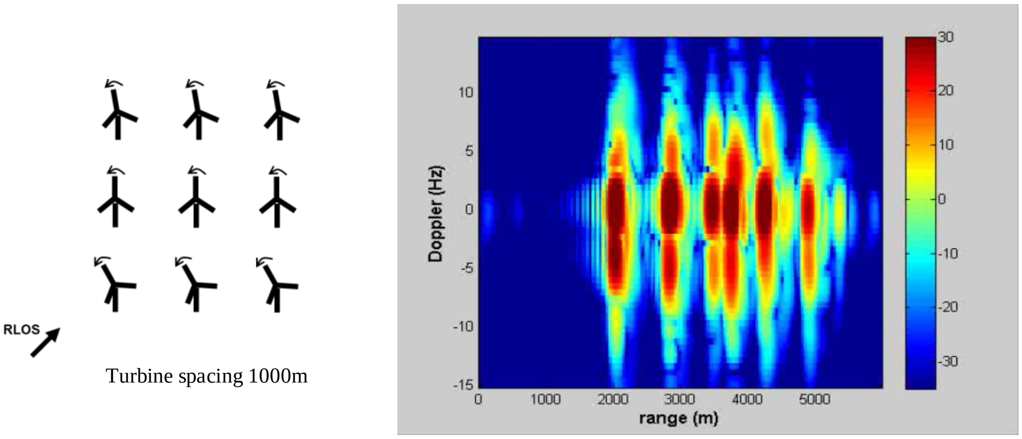


Fig. 7. Range-Doppler plot of the radar clutter from a 3x3 wind farm at 45° from edge-on incidence.

respect to the radar. Overall, we observe wind-farm-induced radar clutter is confined in Doppler to the maximum Doppler of the blades, and in range to the total range extent of the farm.

2.2 Electromagnetic Shadow from a Wind Farm

In addition to examining the radar clutter produced by wind farms, it is also important to study the obstruction (or shadowing) effect produced by wind farms on the potential target (in this case the ocean surface) return. To do so, we simulate the field behind a wind farm at 13MHz using FEKO, and compare the results to the field strength in the absence of the farm. In this study, a static blade structure is assumed, since we expect the tower structure to give the strongest shadowing effect. Otherwise, the same wind farm parameters are used. Fig. 8a shows the field plot (in dB) from a monopole above an infinite conducting plane located on the left at 3000m away from the plot origin. Fig. 8b shows the total field plot in the near field of a 3x1 wind farm. The disturbance of the farm on the field distribution can be observed in the form of (a) a shadow region behind each turbine, and (b) multipath interference outside the shadow zone. Fig. 8c plots the difference between the field strength in Figs. 8a and 8b. From the figure, it can be seen that the depth of the electromagnetic shadow is less than 2dB at this frequency.

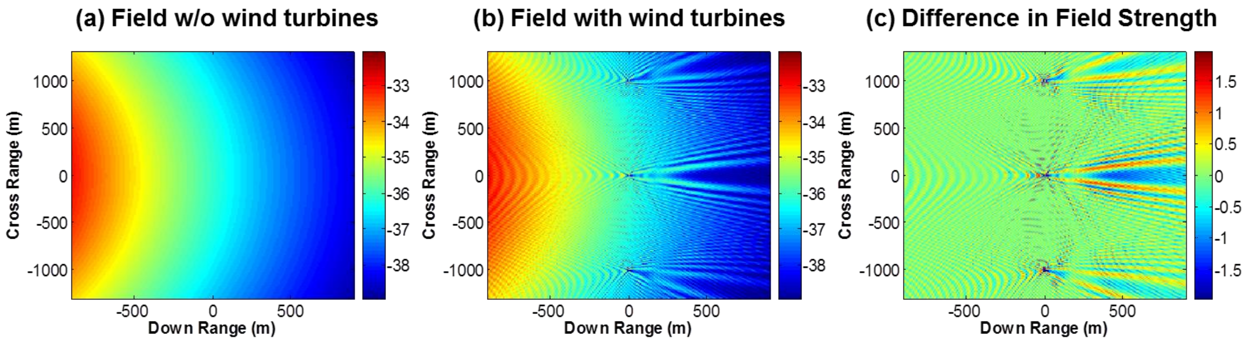


Fig. 8. Shadowing effect of wind turbines. (a) Field without wind turbines. (b) Field with a 3x1 wind farm. (c) Difference in field strength with and without the farm.

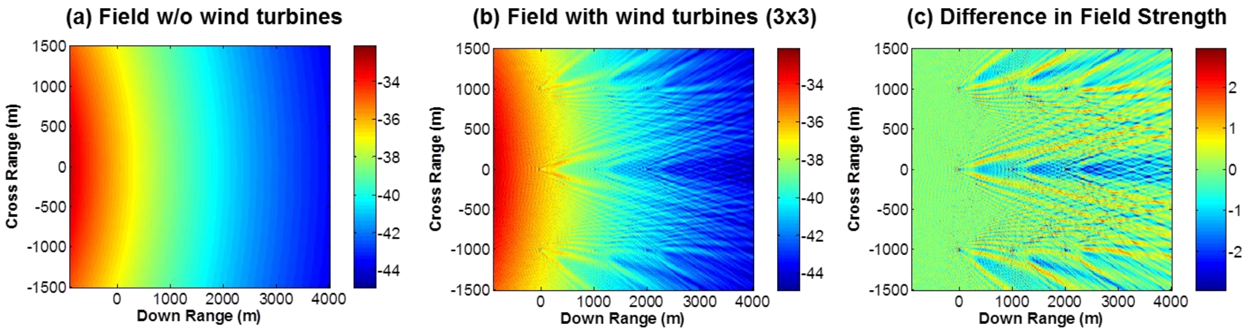


Fig. 9. Shadowing effect of wind turbines. (a) Field without wind turbines. (b) Field with a 3x3 wind farm. (c) Difference in field strength with and without the farm.

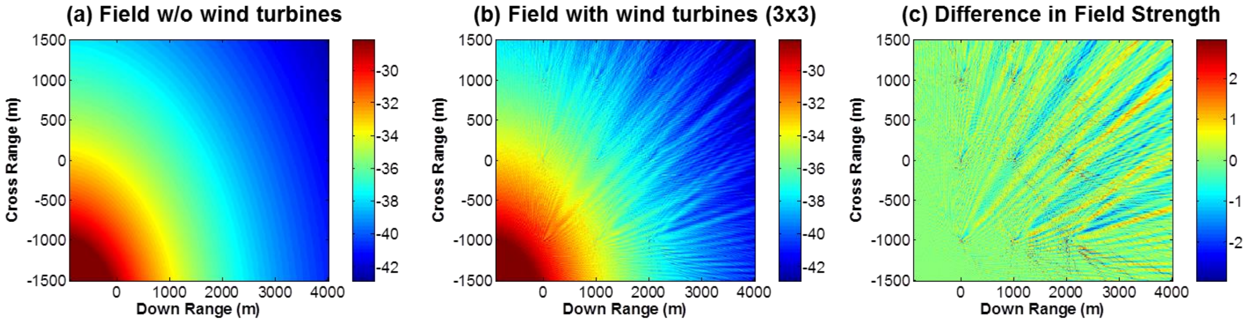


Fig. 10. Shadowing effect of wind turbines under 45° oblique incidence. (a) Field without wind turbines. (b) Field with a 3x3 wind farm. (c) Difference in field strength with and without the farm.

Additional results are generated for a 3x3 wind farm and shown in Fig. 9. Similar to Fig. 8, Fig. 9a shows the field without the farm, 9b shows the total field with the farm, and 9c shows the difference between the two field strengths. The results are similar to those observed in Fig. 8. We do notice a moderate increase in shadow depth for the turbines in the middle row. This means that when a serious of turbines are perfectly lined up with respect the RLOS, the shadowing depth gets progressively darker. However, even in this case, the darkest shadow is still within 2dB of the unperturbed field, and is confined to immediately behind each turbine. Fig. 10 shows the situation for the same 3x3 farm when the radar is moved to a 45 degree oblique angle with respect to the center of the farm. Similar findings are observed.

3. Discussion on Modeling Details

Several issues on the electromagnetic modeling methodology will be discussed in more detail here. First the thin-wire approximation is adopted in this study to save computation time. To address the accuracy of the thin-wire model, we compare the thin-wire result to that from a full surface-mesh model. Figs. 11a and 11b show the range profiles generated from the thin-wire and surface-mesh models, respectively. Figs. 11c and 11d show the range-Doppler plots generated from the thin-wire and surface-mesh models, respectively. It can be concluded that the results from the two types of modeling are very similar. Of course, the thin-wire model takes much less time to simulate (a factor of approximately 40 for a 3x3 wind farm).

Next, we investigate the effect of wire radius in the thin-wire model. To remain within the validity of the thin-wire approximation, the upper limit on the wire radius is $\lambda/80$, or 0.27m at 14MHz. However, as Fig. 12 shows, there does not appear to be a significant change in the RCS level as the wire radius is extended from 0.27m to 1m for the full-surface mesh model. In this case, the 90m tower structure is used in the study. On the other hand, when the thin-wire radius is reduced from 0.27m down to 0.027m then to 0.0027m, there begins to be stronger resonant ringing in range, as shown in Figs. 13a to 13c. This is caused by the strongly guided traveling wave along a very thin wire, which makes multiple traversals along the wire. This traveling wave is not expected to be strong supported in a real turbine structure due to both the larger radius and non-uniform cross section. Therefore, it is recommended that the wire radius be kept at close to its upper limit ($\lambda/80$) for the thin-wire modeling of wind turbines.

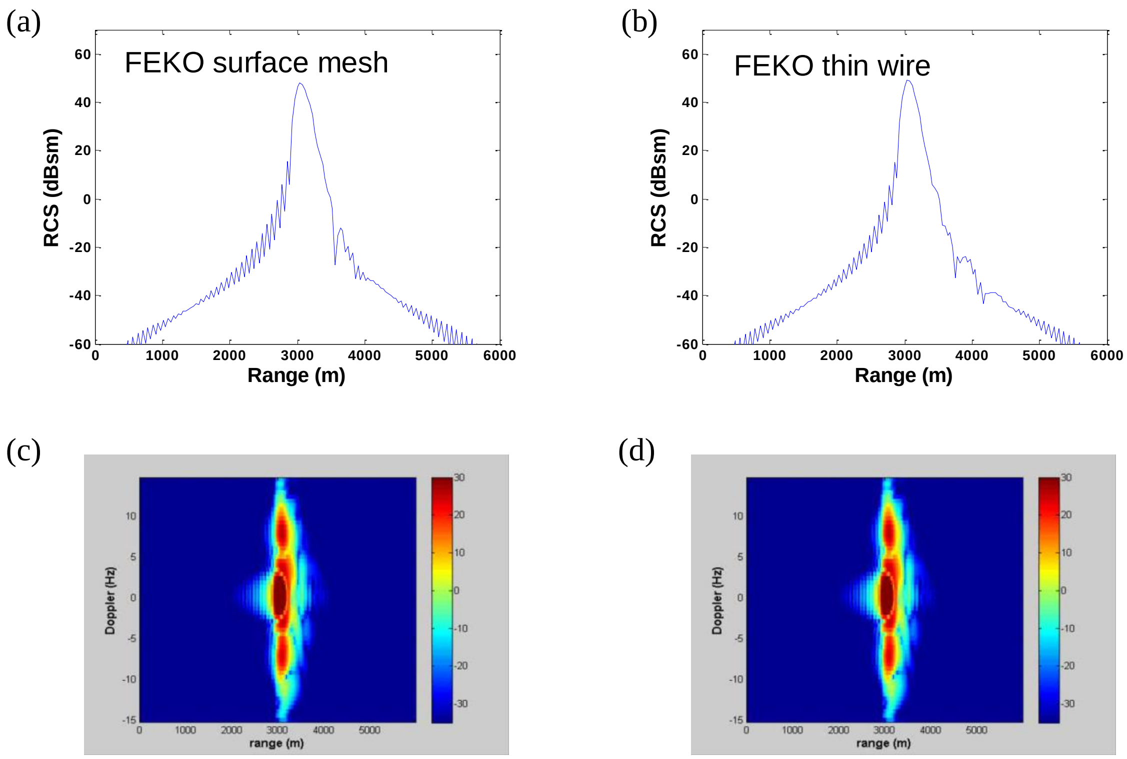


Fig. 11. Comparison between the full surface-mesh model and the approximate thin-wire model computed using FEKO. The blades and tower of the model have a radius of 0.27m. (a) Range profile from the surface-mesh model. (b) Range profile from the thin-wire model. (c) Range-Doppler plot from the surface-mesh model. (d) Range-Doppler plot from the thin-wire model.

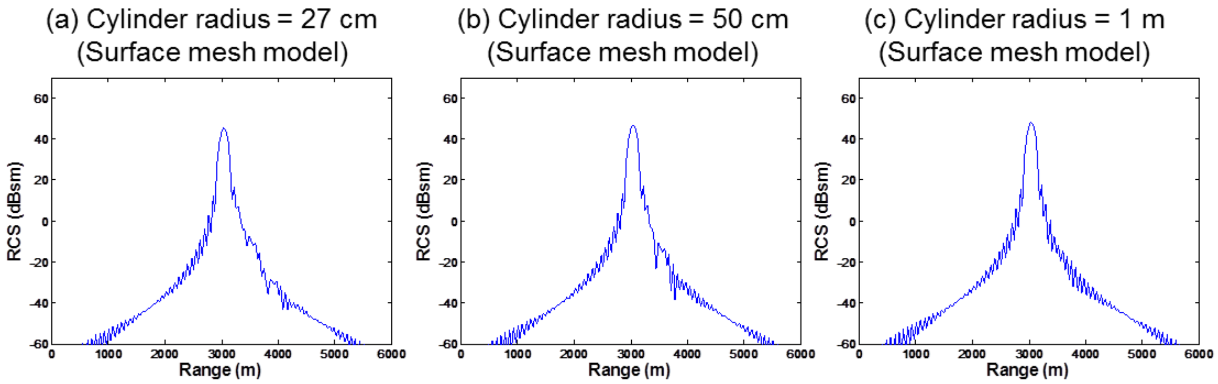


Fig. 12. Effect of increasing the cylinder radius in the surface-mesh model on the range profile of a 90m tower. The frequency range is from 12 to 14 MHz.

Finally, we examine the effect of the ground plane on the observed RCS level. A detailed study on the ground plane effect to wind turbine RCS at microwave frequency range was reported in [5]. Here, we extend the analysis to the HF frequency range. For the configuration at hand where the transmitter is a monopole located on the surface of the ground plane, the scattered field strength is approximately increased by a factor of four from that of the free-standing structure. For the image theory point of view, this comes from the scattering from the original structure and its image due to the real source, and the scattering from the original structure and its image due to the image source. Due to the vertical polarization and the on-surface nature of both the source and the scatterer, these four contributions add coherently in phase. This factor-of-four amplification in field leads to a factor of 16, or 12dB, increase in RCS. Of course, this argument ignores the interaction between the target and its image. Figs. 14a-c illustrates this point. The simulation is conducted both with the ground (Fig. 14a) and without the ground (Fig. 14b). The difference between Fig. 14a and four times Fig. 14b is shown in Fig. 14c. We can see that the difference is small, demonstrating that the approximate 12dB argument is obeyed. Nonetheless, the difference is not zero, as there exist non-negligible higher-order interactions between the turbine and the ground plane.

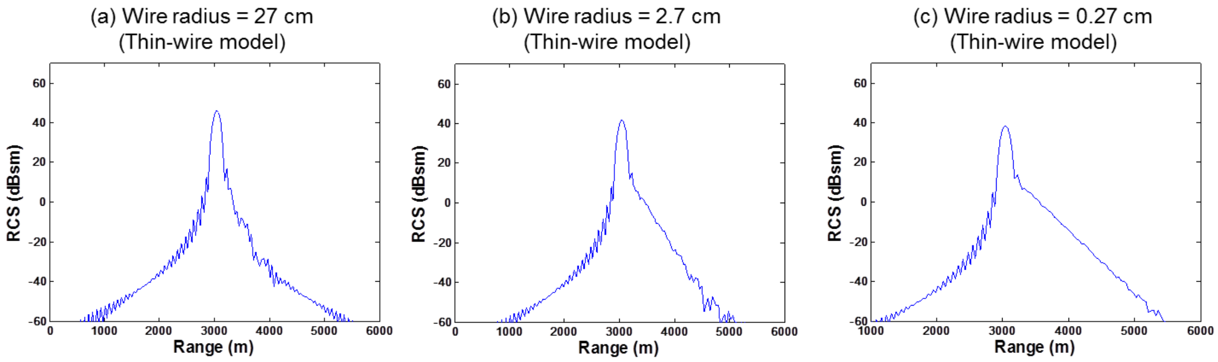

(a) Wire radius = 27 cm (Thin-wire model)
(b) Wire radius = 2.7 cm (Thin-wire model)
(c) Wire radius = 0.27 cm (Thin-wire model)

Fig. 13. Effect of decreasing the wire radius in the thin-wire model on the range profile of a 90m tower. The frequency range is from 12 to 14 MHz.

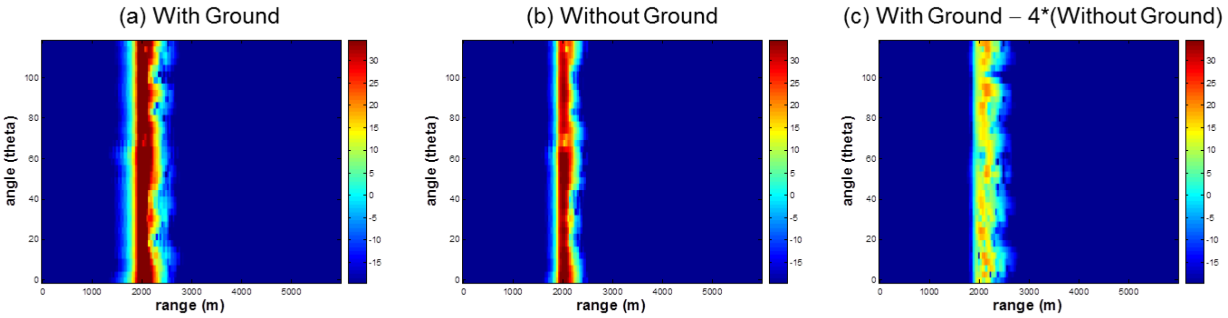

(a) With Ground
(b) Without Ground
(c) With Ground – 4*(Without Ground)

Fig. 14. Effect of ground on the observed RCS level of a single turbine simulated over 120° blade rotation. The frequency range is from 12 to 14MHz. (a) RCS vs. range and blade angle of the turbine with ground. (b) RCS without ground. (c) Difference between the with-ground case and 4x the without ground case.

4. Summary and Assessment

In this study, the electromagnetic interference from offshore wind farms on HF radar has been modeled and analyzed. It was found that:

- Wind farm clutter at HF is sufficiently localized in range. The range extended returns caused by intra- or inter-turbine interactions are weak.
- The Doppler spread of wind farm clutter is limited to the maximum Doppler of the blades, or about ±9Hz at 13MHz. The CODAR system has only a 2Hz sampling rate, so the Doppler spread will be aliased.
- The shadow due to each wind turbine has a shadow depth no greater than 2 dB at HF. The shadow is localized behind each turbine.
- There is a moderate increase in shadow depth behind a turbine that is in the shadow of another turbine.
- The overall shadowing effect of a wind farm is not strong and is localized to the region immediately behind the farm from the radar.

In terms of the strength of the wind farm clutter relative to the desired radar return from the ocean surface, the scattering from the sea surface at HF is approximately given by (0.01)*(range-cross range cell of the radar. Teague and Barrick used a range cell of 3km and a cross range cell of π(15km) (i.e., a semicircle of radius 15km) to come up with an estimate of the ocean return strength of 61.5dBsm. They concluded that when this signal is spread across 20 Doppler frequency bins, the RCS level is at 48.5dBsm. Therefore, the turbine clutter, which is below 30dBsm outside the zero-Doppler bin, may be 18dB below the ocean scattered power. However, the turbine clutter may be comparable to the weaker Bragg lines, or second order signals. Moreover, the turbine clutter will be aliased in Doppler due to the slow PRF (2 or 4Hz) that is typically used in these radars, which compounds the problem. Using higher PRF is a possibility, but it increases the data size and may not be compatible with the current system of using GPS synchronized timing to eliminate interference between multiple CODAR systems. Therefore, our overall assessment is that HF radars may experience interference under certain proximity and operating conditions as the result of typical wind farm configurations. Potential mitigation techniques will need to be investigated once measured wind farm data on HF radar become available in the US.

These additional areas of study are recommended:

1) The present study is based on perfect conducting turbine components. Dielectric blade materials (possibly with internal structures) should be modeled and studied.
2) Field measurements are needed to corroborate the modeling results. The next phase of DOE offshore wind projects may provide a good testing ground to collect HF radar data both before and after installation.
3) Mitigation approaches are possible and should be further researched. For example, the combination of range, azimuth and Doppler filtering may be possible to postprocess the data to remove turbine clutter. Mitigation solution needs to be assessed from both the technical as well as cost point of view.

5. References

[1] L. R. Wyatt and A. M. Robinson, and M. J. Howarth, “Wind farm impacts on HF radar current and wave measurements in Liverpool Bay,” IEEE OCEANS Conference, Santander, Spain, June 2011.

[2] C. C. Teague and D. E. Barrick, “Estimation of wind turbine radar signature at 13.5 MHz,” IEEE OCEANS Conference, Hampton Roads, VA, Oct. 2012.

[3] FEKO version 6.2, Stellenbosch, South Africa: EM Software & Systems Inc. 2012.

[4] J. Jonkman, S. Butterfield, W. Musial, and G. Scott, “Definition of a 5-MW reference wind turbine for offshore system development,” National Renewable Energy Laboratory, Tech. Rept. NREL/TP-500-38060, Feb. 2009.

[5] A. Naqvi, N. Whitelonis and H. Ling, “Doppler features from wind turbine scattering in the presence of ground,” *Progress in Electromag. Research Lett.*, vol. 35, pp. 1-10, 2012.

Appendix C1.4

Modeling Study on the Effect of Offshore Wind Farms on Communications Systems

1. Scope of Study

In addition to their potential impact on radar systems, offshore wind farm structure may also affect communications systems operating in the marine environment. This includes vessel-to-vessel, vessel-to-shore and vessel-to-space links. Examples of systems that potentially may be affected include satellite links such as GPS (global positioning system, 1.6GHz) for navigation and Iridium (1.6GHz) and GOES (400MHz) for data relay by various ocean monitoring sensors, VHF (160MHz) radios for marine communications, and AIS (160MHz, automatic identification system) for vessel tracking. Past studies on the potential interference due to land-based wind farms have focused on TV transmission in the UHF band [1, 2]. During the construction of the Horns Rev offshore wind farm in Denmark, VHF radio operation was tested, with no observable effects reported [3]. Similarly, a fairly comprehensive study was conducted in North Hoyle wind farm off the coast of UK, and no significant impact on GPS and VHF communications systems was observed [4].

In this study, we carry out the modeling of the propagation channel when the transmitter (or receiver) is located within or around a wind farm in order to assess the effect of multipath and shadowing on communications systems that are operated within the offshore wind farm environment (see Fig. 1). This report is organized as follows. In Sec. 2, we present a computational methodology to simulate the near field distribution around a wind farm. In Sec. 3, we present results of the simulation at various frequencies of interest. Our summary and assessment are presented in Sec. 4.

2. Modeling Methodology

A number of analytical and numerical approaches have been applied to model the wind farm blockage problem. A simple, approximate geometrical blockage estimate can be derived based

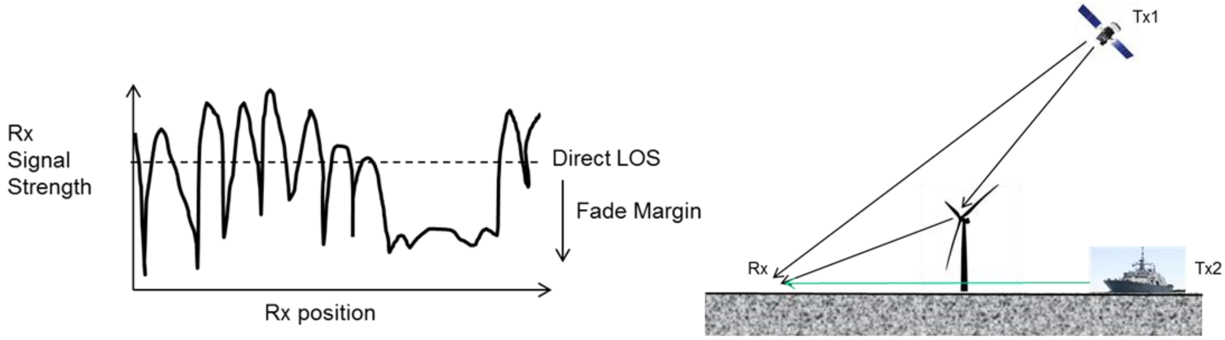
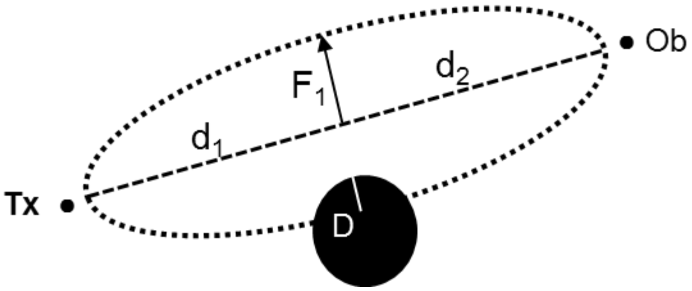


Fig. 1. Illustration of communications channels encountered in the marine environment.



$$F_1 = \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}}$$

$$\frac{E^{tot}}{E^i} = 1 - \frac{D}{F_1}$$

Fig. 2. Fresnel zone blockage calculation used in [5], [6], [7] for assessing wind turbine blockage.

on the Fresnel zone argument, as shown in Fig. 2 [5]. This is the standard methodology used to estimate the shadowing effect due to wind turbine structures by the Federal Aviation Administration obstruction evaluation process [6, 7]. Full-wave analysis was used to analyze the shadow due to a turbine tower under a pencil beam excitation in [8]. Finally, Xpatch, which was the simulation tool used in Appendices C1.1 and C1.2, can be modified to compute the near field distribution around a wind farm. However, the computation time required to analyze a large wind farm can be prohibitively high.

Here we adopt a more efficient but approximate electromagnetic approach to compute the received field strength within and around a wind farm. Our approach is based on several simplifying assumptions. First, the turbine scattering is assumed to be dominated by the tower structure of the turbine, while additional scattering from the blades and nacelle structures are assumed to be of secondary importance. Second, due to the large length-to-cross section ratio of typical tower structures, the scattering process is assumed to be predominately two-dimensional (2-D) in nature for an observer located close to the turbine. Third, we assume that the scattered fields can be predicted by using the far-field complex echo width (EW) of the tower. Lastly, the individual turbines in a wind farm are assumed to be excited under the incident excitation while neglecting the interaction terms. This is also known as the Born approximation. Using these assumptions, we arrive at an approximate prediction methodology that leads to a significant reduction in the computational complexity of the problem and allows us to predict the shadow and multipath interference within and around a large wind farm. Detailed description of the approach can be found in [9].

First, the result of the geometrical simplification is studied. Fig. 3a shows the resulting near field distribution due to a plane wave incidence around a single turbine at 500MHz. The result is computed using the multi-level fast multipole method (MLFMM) in the commercial electromagnetic package FEKO [10]. The turbine model consists of a long cone-shaped tower, a rectangular-shaped nacelle and turbine blades which are modeled by thin plates. The tower is 64.5m tall with a 3.8m bottom diameter and 2.8m top diameter. The nacelle is 15m long and has a 3m x 3m cross section. The three turbine blades are modeled as 34.3m long and 3m wide plates with a 15° pitch angle with respect to the rotation plane. All three components are assumed to be perfect conductors for simplicity. The structure resides on an infinite, conducting plane, which is

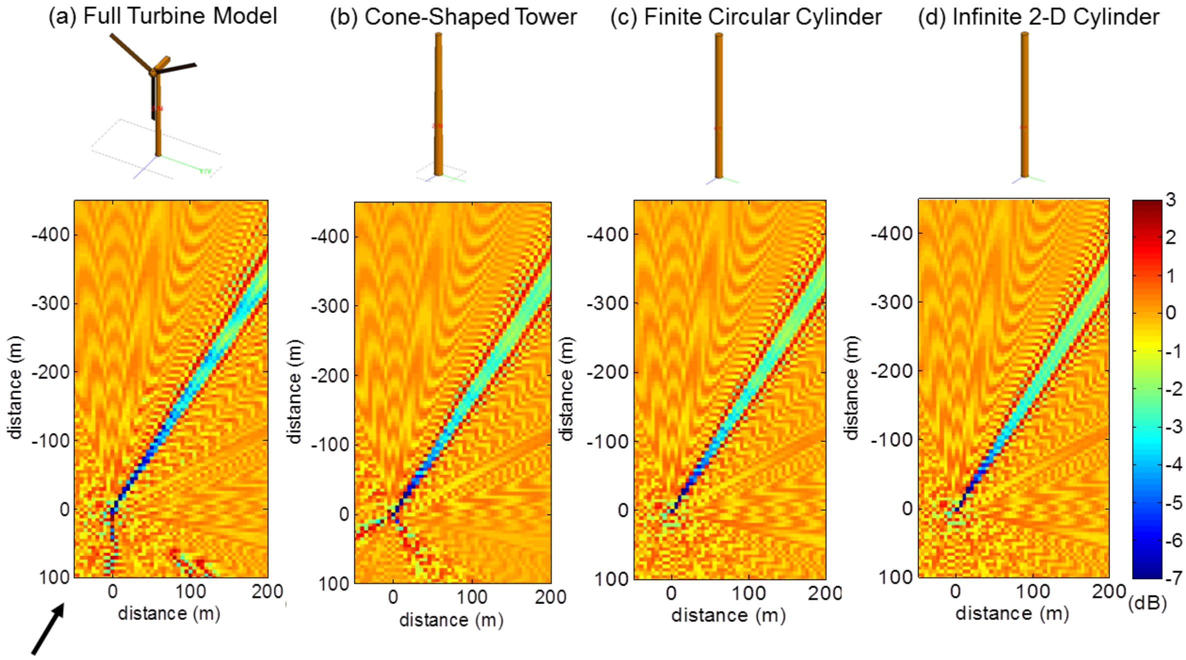


Fig. 3. Results of the single-turbine simulation at 500MHz. (a) Near-field distribution around a 3-D turbine model including the tower, nacelle and blades. (b) Near-field distribution around the cone-shaped tower. (c) Near-field distribution around a 3-D finite cylinder. (b) Near-field distribution around an infinite 2-D cylinder.

used to model the ocean surface. The turbine is excited with a plane wave at zero elevation and 30° with respect to hub-on incidence in azimuth. The incident wave is vertically polarized. The resulting total electric field in the vertical polarization is plotted at zero height in the xy-plane with a sampling interval of 5m in Fig. 3(a). The turbine is located at x=y=0. The field strength is normalized with respect to that without the turbine structure and plotted in dB with a dynamic range of 10dB. A shadow region behind the turbine is clearly observed. The shadow is darkest immediately behind the turbine, but gradually disappears as the distance increases. Outside the shadow region, rapidly oscillating interference patterns are observed.

Figs. 3b-3d show the consequence of a series of geometrical simplifications. Fig. 3b shows what happens when only the tower is considered. The result shows an RMS error in the field intensity of 1.98% when compared to the full model in Fig. 3a. Fig. 3c shows when the cone-shaped tower is replaced by a circular cylinder with a radius of 3.3m, which corresponds to the averaged radius of the cone-shaped tower. The RMS error with respect to the full model is increased to 2.14%. Fig. 3d shows when the cylinder is assumed to be infinitely long, and the problem is simulated as a 2-D electromagnetic structure. The RMS error is only slightly increased further to 2.18%. Therefore, the features of the turbine scattering can be mostly captured by that from a simplified 2-D cylinder, while the computational load is dramatically reduced.

Computing the near field at many sampling points at 1GHz and above is still computationally demanding since the computation time scales as the product of the number of observation positions and the number of current basis functions. To further reduce the computation time for

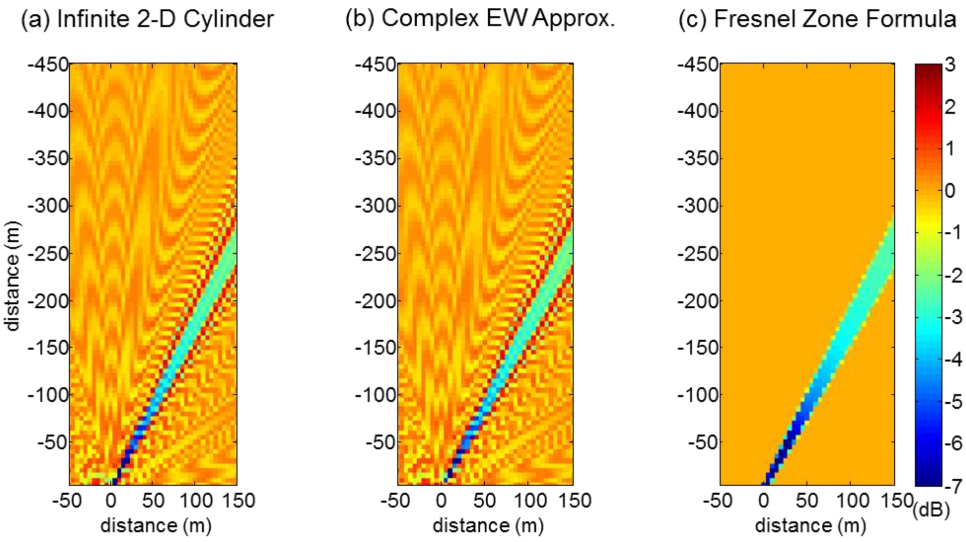


Fig. 4. Computed near-field distribution around an infinite 2-D cylinder at 500MHz. (a) Brute-force numerical integration. (b) Complex echo width (EW) approximation. (c) Fresnel approximation.

the near field, we use the 2-D far-field approximation to compute the 2-D scattered field. Both amplitude and phase information of the complex echo width from the cylinder are computed and stored. We then compute the total field by adding the incident plane wave to the scattered field, which is constructed by the complex EW with the proper space decay and phasing as follows:

$$E^s = E^i \frac{e^{-jkr}}{\sqrt{2\pi r}} \sqrt{EW}\, e^{j\,[phase(EW)]} \tag{1}$$

The resulting near-field distribution computed using this approach is shown in Fig. 4b for a 2-D cylinder. When compared to the brute-force results in Fig. 4a, the RMS error introduced by this approximation is only 1.44%. Note that the complex EW approximation requires the distance to be farther than $2D^2/\lambda$, where D is the cylinder diameter. In this case, that distance is 36.5m, which is quite close to the structure. For comparison, we also compute the forward shadow using the Fresnel zone blockage formula described in [5-7]. The attenuation of the incident field at a position directly behind the turbine is estimated by $1\text{-}D/F_1$ in linear scale, where F_1 is the first Fresnel zone radius, which is given by:

$$F_1 = \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}} \tag{2}$$

where λ is the operating wavelength, d_1 is the distance from the transmitter to the cylinder and d_2 is the distance from the cylinder to the observation position. The Fresnel shadow is presented in Fig. 4c. It is observed that the shadow width is properly predicted but the shadow is too dark. Also, this approach cannot be extended to predict the interference pattern outside the shadow region. The RMS error between Figs. 4c and 4a is 8.24%.

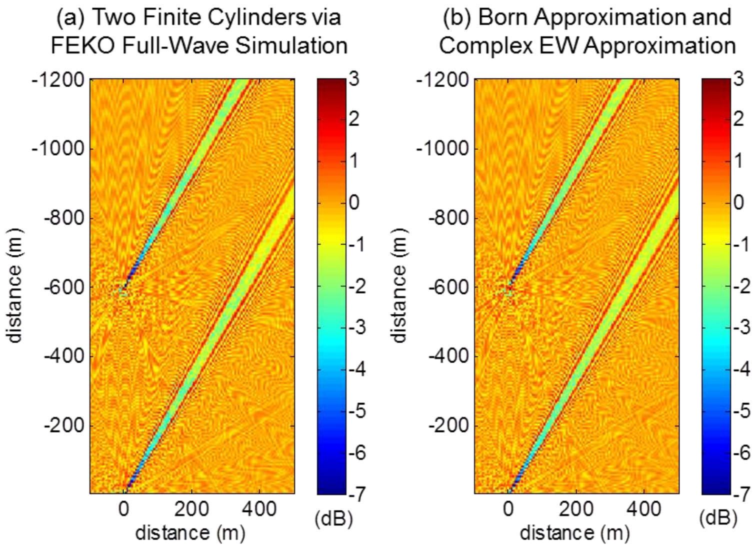


Fig. 5. (a) Near-field distribution around two finite 3-D cylinders at 500MHz computed using the full-wave solver. (b) Near-field distribution around two infinite cylinders generated using the complex EW and Born approximations.

To extend the approach to a wind farm consisting of tens or hundreds of turbines, we apply the Born approximation and assume each turbine is fully illuminated by the incident field. This approximation is expected to be least accurate when the turbines are lined up, so that one turbine casts a shadow over subsequent turbines. However, this scenario exists only at very few incident angles, considering the slenderness of the turbine structure and the large spacing between turbines found in offshore wind farms (600-1000m). To test whether the Born approximation is reasonable, two 64.5m long, finite cylinders located on top an infinite, conducting ground plane, each with a 3.3m diameter and spaced 600m apart, are simulated rigorously using FEKO's MLFMM solver at 500MHz. The near-field result is plotted in Fig. 5a. The Born approximation in conjunction with the 2-D modeling and the complex echo width approximation discussed in the last section are applied to generate the result plotted in Fig. 5b. It is seen that both the shadow region and the interference pattern agree quite well with those in Fig. 5a. The RMS error between Figs. 5a and 5b is 2.15%.

To summarize, we have developed an approximate methodology to model the near field distribution within and around a wind farm. The approximations entail geometrical simplifications, near field computation using the 2-D complex echo width, and the Born approximation. These steps lead to a significant speedup in the computation time without a significant loss of accuracy.

3. Results

Based on the above methodology, the near field distributions around a 3x3 wind farm with a 600m spacing between turbines is computed on the surface of the ground plane at 150MHz, 500MHz, 1.5GHz and 3GHz. These results assume that the transmitter is in the far field at an elevation angle of 0°, which is representative of long-distance vessel-to-vessel or vessel-to-land

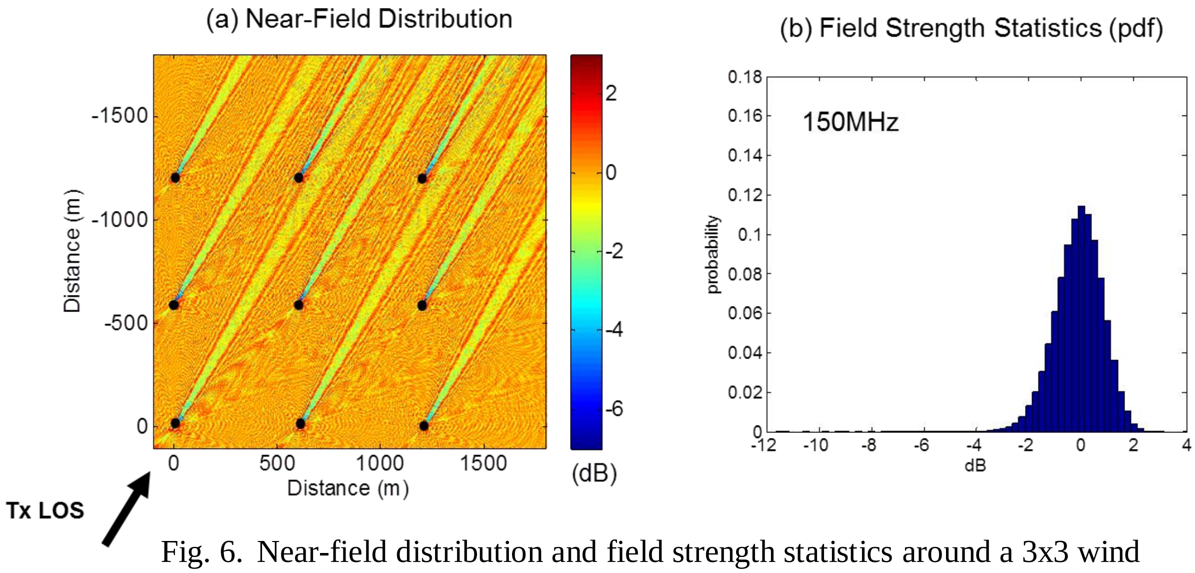


Fig. 6. Near-field distribution and field strength statistics around a 3x3 wind farm at 150MHz.

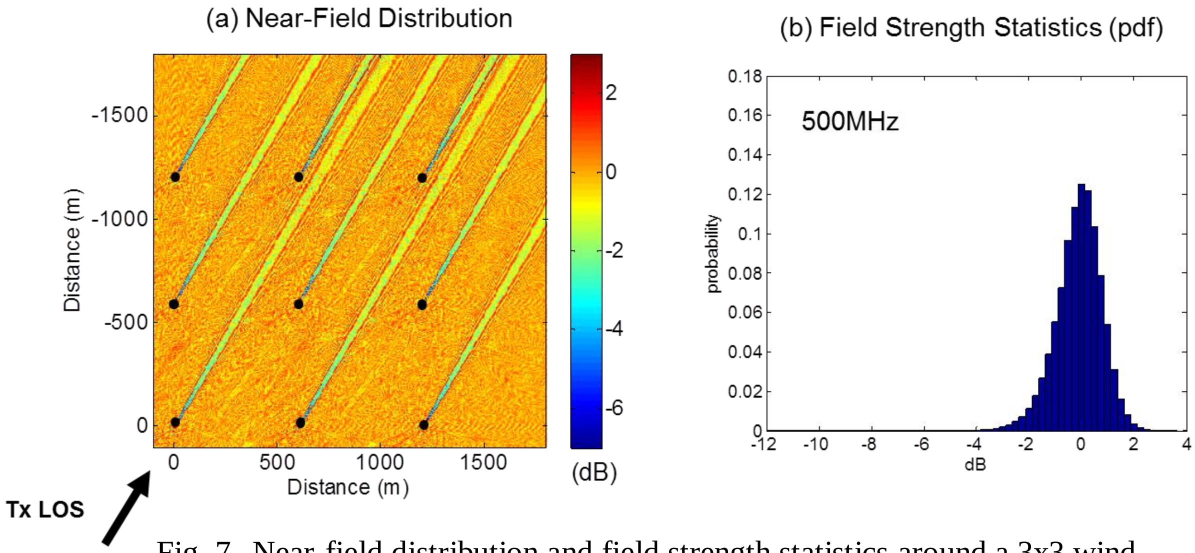


Fig. 7. Near-field distribution and field strength statistics around a 3x3 wind farm at 500MHz.

communications. The results are shown in Figs. 6, 7, 8 and 9, respectively. Fig. 6a shows the near-field distribution while Fig. 6b shows the statistics of the field strength, tabulated into the form of a probability density function. At 150MHz, it can be observed that dark shadow occurs only when the observation position is within 100m of the back of the turbine with respect to the incident direction. The field strength in the shadow region as we move farther away from the turbine becomes almost the same as the field strength outside the shadow region. As the frequency is increased, the shadow becomes darker and extends farther in range. This follows the expected trend since the shadow should eventually approach the geometry optics limit in the very high frequency limit. However, the shadow depth is less than 6dB relative to the line-of-sight signal even at 3GHz. The multipath interference pattern also becomes more rapidly

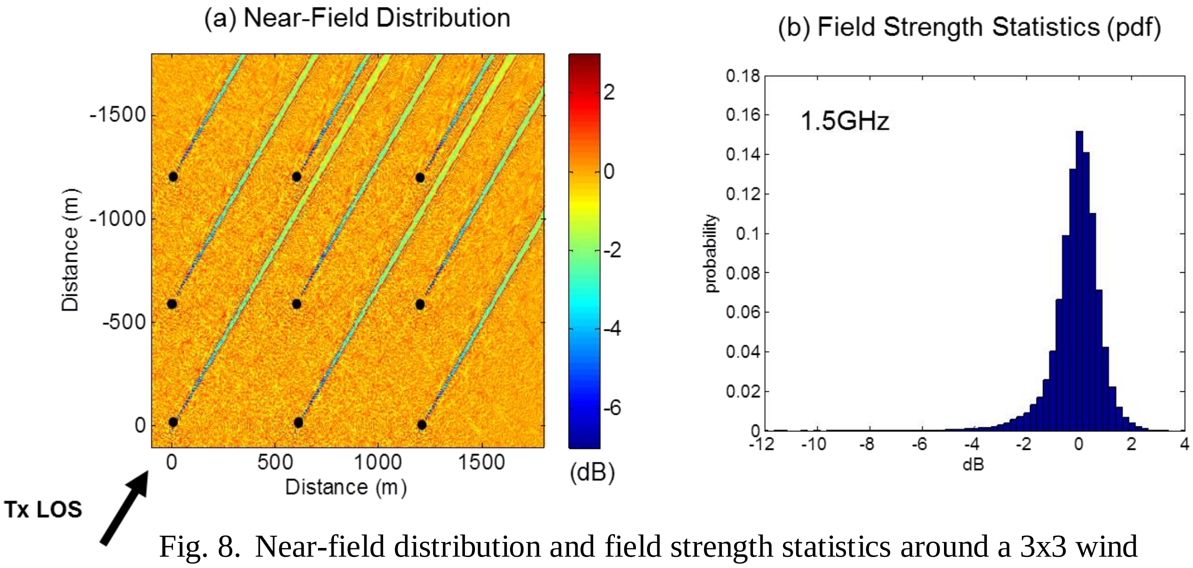


Fig. 8. Near-field distribution and field strength statistics around a 3x3 wind farm at 1.5GHz.

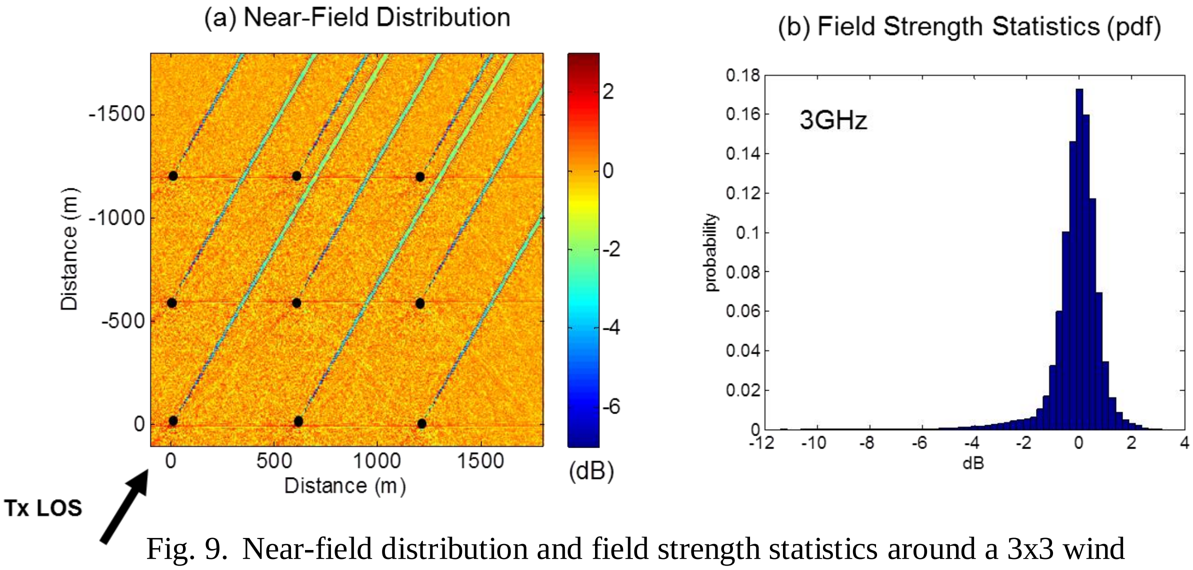


Fig. 9. Near-field distribution and field strength statistics around a 3x3 wind farm at 3GHz.

changing as a function of position. Based on the signal statistics in Figs. 6-9(b), we tabulate that there is a 99% probability that the signal fade in the vicinity of the wind farm is no worse than 2.6dB at 150MHz, 2.7dB at 500MHz, 3.4dB at 1.5GHz, and 3.7dB at 3GHz. Given the 10 to 15dB link margin typically built into communications systems, this implies the fading will not be a serious issue unless the system comes extremely close to the turbine.

Several additional scenarios are considered here. First is the case when the transmitter is moved closer to the wind farm, as in the vessel-to-vessel communications case. Previous results assume the transmitter is sufficiently far for the incident field to be considered a plane wave in the

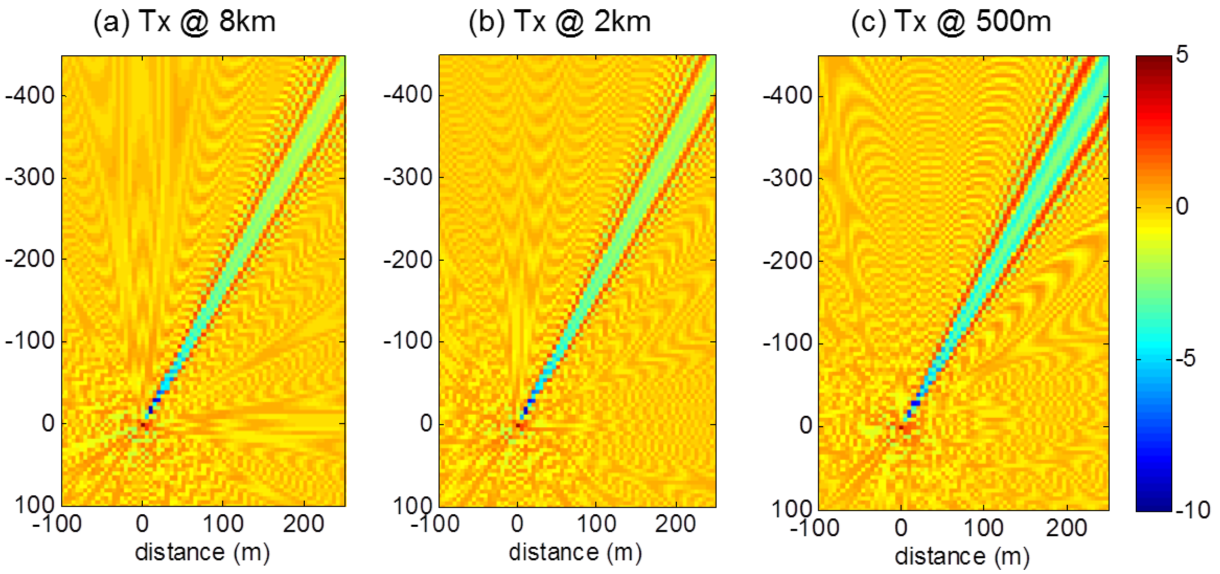


Fig. 10. Near-field distributions for different transmitter distance from the wind turbine. The field strength at each position is normalized by the incident field strength.

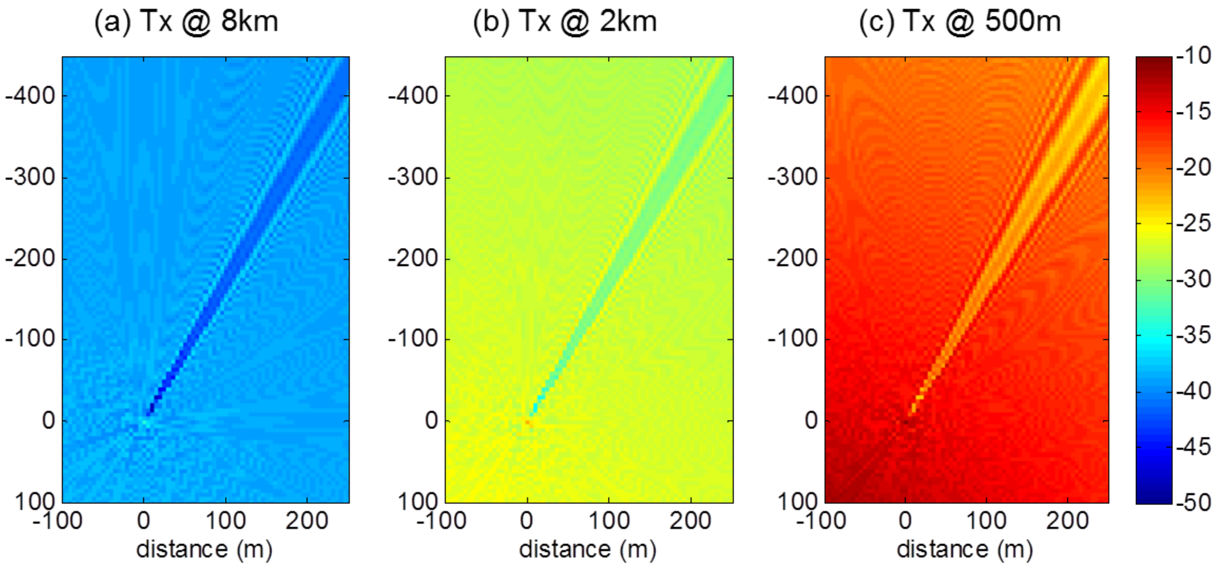


Fig. 11. Near-field distributions for different transmitter distance from the wind turbine. The field strength at each position is normalized by the transmitted power.

neighborhood of the turbine. Figs. 10a, 10b and 10c show the FEKO simulation results when the transmitter is moved from respectively, 8km to 2km to 500m from a single wind turbine. The simulation is carried out without any approximation at 500MHz. Unlike earlier plots, the plotted field strength at each position is normalized by the incident field strength. Across the three figures, we observe that the shadow appears to get deeper, broader and longer as the transmitter is moved closer to the tower. While this is true on a relative scale, the picture is different on an absolute scale, as shown in Figs. 11a, 11b and 11c. In this case, the field strength in the plot is normalized to the transmitted power. It can be seen that in the close-in transmitter case of Fig. 11c, the overall signal strength is much stronger even though the shadow relative to the LOS signal is deeper. Therefore, the close-in transmitter case would pose less of a detrimental effect to the communications system.

Second, we discuss the case when the transmitter is not at zero elevation with respect to the wind farm, as were the results presented thus far. This scenario occurs in the vessel-to-air and vessel-to-space propagation channel. Fig. 12a shows the shadow region behind a finite tower in the vertical cut plane along the incident field direction for an incident elevation angle of 0°. The tower is modeled by a circular cylinder that spans z=[-32.25m, +32.25m]. For simplicity, no conducting ground plane is assumed. The model is run at 500MHz using FEKO's MLFMM solver. It is observed that the field strength in the shadow is relatively uniform at different observation heights along the tower. A shadow boundary at the top edge of the tower is noted, in agreement with the optical shadow intuition. Fig. 12b shows the case of a plane wave incident at 30° elevation angle. The shadow boundary is now tilted. If we confine the observation position to along the z=0 plane, the dark shadow region is now much shorter as we move away from the tower. This implies that the zero-elevation results can provide a conservation estimate of the shadowing effect from wind turbines. We should note that in the presence of a reflecting ocean surface, additional surface reflections can occur, as discussed in [11]. However, these additional interactions should not significantly change the conclusions reached here.

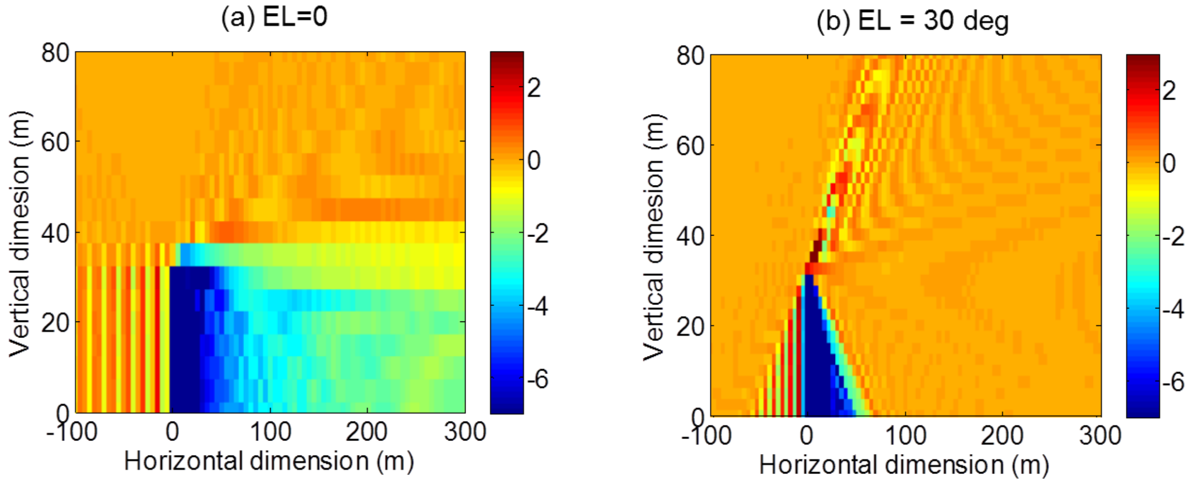


Fig. 12. Near-field distributions along the vertical plane. (a) Transmitter at zero elevation. (b) Transmitter at 30° elevation.

Lastly, we consider the case when multiple turbines are lined up. In this case, the Born approximation is not expected to give accurate results. Figs. 13a and 13b show the shadows behind, respectively, one stand-alone turbine and two lined-up turbines. They are computed without any approximation using FEKO at 500MHz. It is apparent that the shadow becomes much darker behind the second turbine in Fig. 13b. This result is consistent with the measurement taken in King Mountain, TX reported in [12]. This phenomenon could potentially

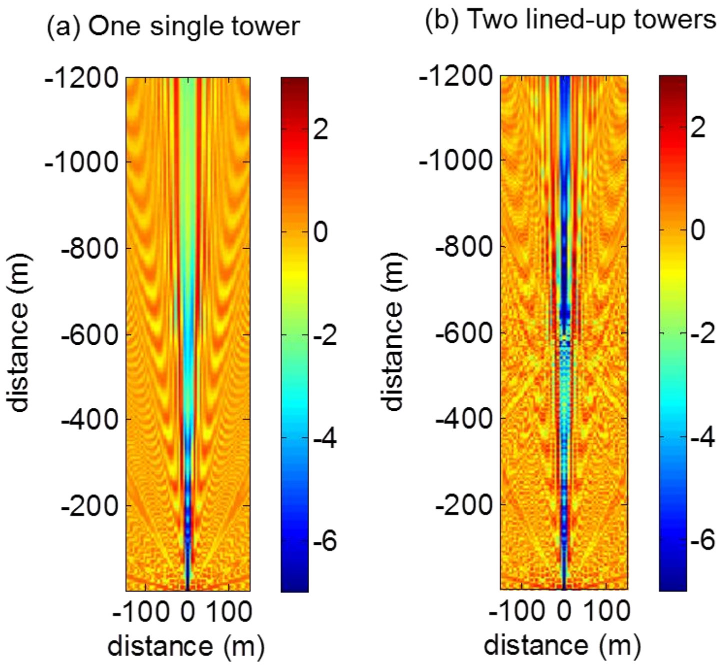


Fig. 13. Full-wave FEKO simulation of the near field distributions at 500MHz. (a) A single tower. (b) Two lined-up towers.

lead to darker shadow regions when multiple turbines on a farm are lined up with respect to the transmitter. However, this situation should be quite rare given the slenderness of the turbines and the spacing between turbines on a farm. Nevertheless, this behavior should be a consideration during the planning for wind farm layouts or the siting of onshore communications stations.

A few final remarks are in order. It is noted that the results for the reciprocal link, i.e., with the transmitter inside the farm and receiver outside the farm, should be exactly the same due to electromagnetic reciprocity. Second, the vertical polarization is considered throughout the study, while other polarizations are also employed in communications systems. However, due to the large size of the tower diameter relative to the wavelengths of interest, we expect the results to be fairly independent of polarization. Lastly, no consideration has been given to Doppler effects due to the rotating turbine blades in this study. Although such effect is expected to be small in the shadow region, its effect to the multi-path region in the form of time-varying fading should be examined.

4. Summary and Assessment

In this study, the electromagnetic interference from offshore wind farms on communications systems operating in the VHF to microwave range has been modeled and analyzed. It was found that:

- A distinct shadow region is observed behind the tower. Multipath interference is observed outside the shadow region.
- The shadow becomes more optical-like as frequency is increased, leading to longer, narrower and deeper shadows. However, the signal fade is still less than 6dB relative to the direct LOS signal up into the GHz range.
- The vessel-to-vessel link can serve as a worst-case estimate of the vessel-to-satellite link.
- The shadow becomes deeper when more than one turbine is lined up with respect to the Tx LOS. However, this situation is rare.

Our assessments on the effect of wind farms on marine communications are as follows:

1) Most communications systems have built-in link margins to combat signal fading. For example, typical GPS receivers have a fade margin of 15dB or greater.
2) Given the small degree of the signal fade (<6dB) and the finiteness of the electromagnetic shadow found around wind farms, the effect of wind farms on communications systems is expected to be low.
3) When more than one turbine is lined up with respect to the Tx LOS, the fading risk is elevated.
4) The disruption on phase due to wind farms may cause some concerns on those applications where phase information is used, such as direction finding and precise GPS relative and absolute positioning techniques based on carrier phase measurements. These should be further examined.
5) For radar, the shadowing factor computed in this study should be doubled (from 6dB to 12dB) to account for the two-way propagation loss. This may lead to some loss in detection range when either the target or the radar is in the deep shadow of the turbine. However, this is still limited to be a small region behind the tower.
6) Future measurement data collection is recommended to corroborate the results of this simulation study.

5. References

[1] D. L. Sengupta and T. B. A. Senior, “Electromagnetic interference to television reception caused by horizontal axis windmills,” *Proc. IEEE*, vol. 67, pp. 1133-1142, Aug. 1979.

[2] I. Angulo, D. de la Vega, O. Grande, N. Cau, U. Gil, Y. Wu, D. Guerra, and P. Angueira, “Empirical evaluation of the impact of wind turbines on DVB-T reception quality,” *IEEE Trans. Broadcasting*, vol. 58, no.1, pp.1-9, Mar. 2012.

[3] “Report on Horns-Rev VHF radio and marine radar,” Elsam Engineering, DK report to Cap Wind Associates, Doc. No. 186829, Mar. 2004

[4] M. Howard and C. Brown, “Results of the electromagnetic investigations and assessments of marine radar, communications and positioning systems undertaken at the North Hoyle wind farm,” QinetiQ and the Maritime and Coastguard Agency, QINETIQ/03/00297/1.1, MCA Report MNA 53/10/366, Nov. 2004.

[5] *Assessment Methodology to Determine the Impact of Wind Turbines on ATC Surveillance Systems*, European Organisation for the Safety of Air Navigation, Eurocontrol Doc ID 0.3, May 2007.

[6] J. J. Lemmon, J. E. Carroll, F. H. Sanders, and D. Turner, "Assessment of the effects of wind turbines on air traffic control radars," National Telecommunications and Information Administration Tech. Rept. 08-454, Dept. of Commerce, July 2008.

[7] S. Hawk, "Impact study of 130 offshore wind turbines in Nantucket Sound," FAA Western Service Area Engineering Services, Report AJW-W15B, Mar. 2009.

[8] G. Greving and M. Malkomes, "Weather radar and wind turbines – an update of the theoretical and numerical analysis of effects," in *Proc. 6th European Conference in Meteorology and Hydrology*, 2010, pp. 1-5.

[9] S. T. Yang and H. Ling, "Electromagnetic simulation of the near-field distribution around a wind farm," *Int. J. Antennas Propagat.*, special issue on Impact of Wind Farms on Radiocommunication Systems, vol. 2013, Article ID 105071, 9 pages, 2013.

[10] FEKO version 6.2, Stellenbosch, South Africa: EM Software & Systems Inc. 2012.

[11] A. Naqvi, N. Whitelonis and H. Ling, "Doppler features from wind turbine scattering in the presence of ground," *Progress in Electromag. Research Lett.*, vol. 35, pp. 1-10, 2012.

[12] S. Jordan, "Test report for evaluation of wind turbines impact on long-range radar surveillance at King Mountain, Texas," 84th Radar Evaluation Squadron, Hill Air Force Base, Mar. 2008.

Appendix C2: Modeling underwater noise due to offshore wind farms

1 Introduction

In this appendix the generation and propagation of underwater sound due to the vibration of towers supporting off-shore wind turbines is considered. The generation of sound waves by arrays of vibrating wind turbine towers, and the propagation of that sound into the deep ocean at several potential wind farm locations along the mid-Atlantic seaboard, is estimated. The source model that was developed for this effort is outlined in Sec. 2, simulation parameters are explained in Sec. 3, and simulation results for constant-depth and deep sea environments are presented in Sec. 4.

Mechanical vibrations due to rotation of the wind turbine and gears in the gearbox travel from the nacelle and down the support tower before entering the portion of the tower surrounded by the water column and seabed. Contact with the water column and seabed cause radial motion of the tower to generate sound waves which enter the water column and ultimately propagate into deep ocean. The energy associated with these vibrations is tonal in nature and is correlated closely with harmonics of the rate at which gear teeth impact one another.[1]

Two complementary models were employed in this effort. The first is a model based on wave number integration which was developed as a source model to estimate the sound pressure field near a vibrating wind turbine tower. This model is limited to turbines supported by towers (as opposed to floating platforms) and was used to propagate the sound field to a range of 10 km from the wind farm over a horizontally stratified bathymetry, i.e., the bathymetry is independent of distance from the tower. At distances where horizontal stratification ceases to exist, the sound field predicted by the source model is coupled to a parabolic equation (PE) code for propagation off the continental shelf and into the deep ocean.

1.1 Source model[2]

The geometry of the source model is shown in Fig. 1. The pulsating tower is modeled as a vertical line array of volume sources in both the water column and the sediment layers, an approximation which has been employed to model underwater noise generation by pile driving.[3] The following contributions to the sound field in the water column are included in the source model (corresponding to the numbered paths in Fig. 1):

1. Radial vibration of the portion of the tower in the water column
2. Radial vibration of the portion of the tower in the sediment layers resulting in compressional and shear waves which are transmitted into the water column
3. Propagation of the interface (Scholte) wave along the sediment-water boundary

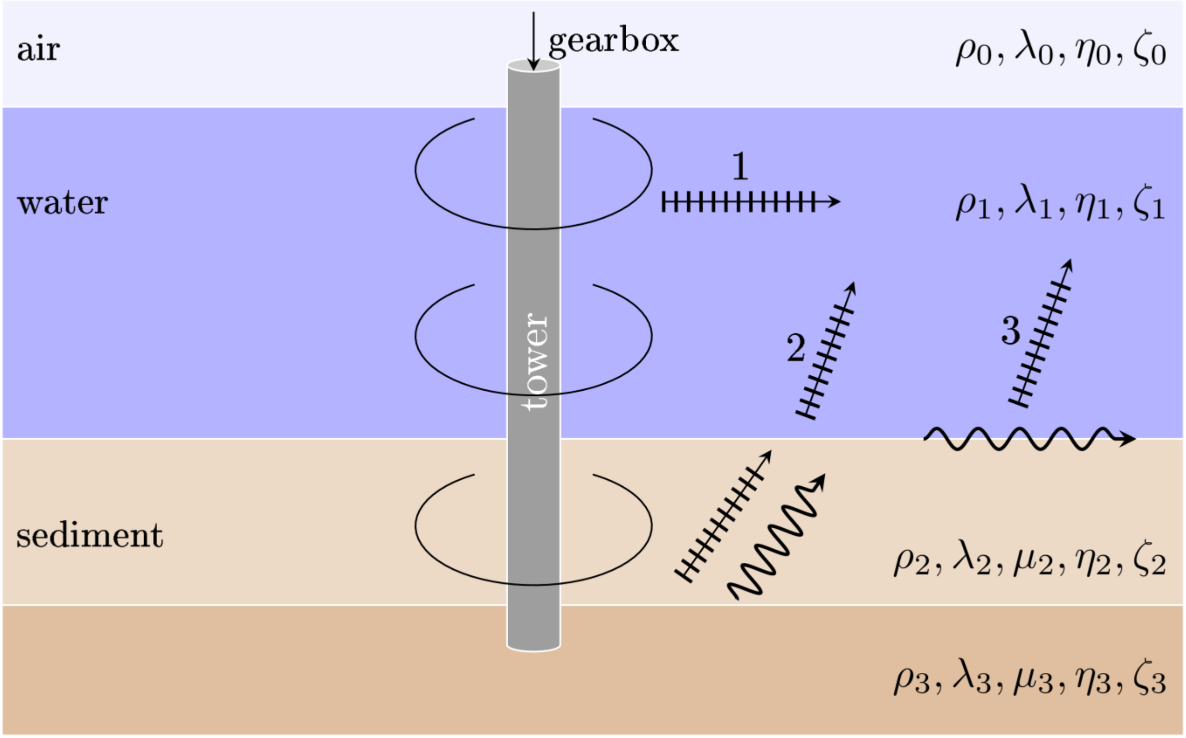


Figure 1: Source model geometry

1.2 Long range sound propagation

In order to simulate sound propagation into deep ocean a PE model was implemented with the output of the source model used as an initial condition. A version of the range-dependent acoustic model (RAM) was implemented to simulate propagation over range-dependent bathymetries with depth- and range-dependent sound speeds.[4;5]

2 Source Model Theory

The tower is approximated as an ensemble of independent volume sources arranged in a vertical line positioned in the water column and seabed along the z axis. For the source model the air, water and sediment layers are assumed to be infinite in the x-y plane but have finite thicknesses along the z axis perpendicular to the interfaces. The layers have densities ρ_j, longitudinal (compressional wave) sound speeds $c_{l,j}$, transverse (shear wave) sound speeds $c_{t,j}$, shear moduli μ_j, shear viscosities η_j, and dilitational viscosities ζ_j. See Fig. 1.

Boundary conditions requiring continuity of displacement and stress are imposed at each interface, and the Green's function for pressure due to each volume source along the z axis has been derived. See Ref. 6 for details. Due to symmetry the Green's function is a function of depth z and range only, and therefore may be decomposed into an angular spectrum in the x-y plane.[6]

The pressure due to a single pulsating tower P_{tower} may be calculated by performing a numerical inverse Hankel transform and then numerically integrating the Green's function along the z axis.

Complex wave numbers for longitudinal and transverse motion, $k_{l,j}$ and $k_{t,j}$, may be expressed as

$$k_{l,j} = \omega\sqrt{\frac{\rho_j}{\lambda_j + 2\mu_j}\left(1 + i\frac{\alpha_{l,j}}{2\pi}\right)}, \quad k_{l,j} = \omega\sqrt{\frac{\rho_j}{\mu_j}\left(1 + i\frac{\alpha_{t,j}}{2\pi}\right)} \tag{1}$$

where $\alpha_{l,j}$ and $\alpha_{t,j}$ are loss factors (in Np/wavelength) for longitudinal and transverse waves, respectively, in the j^{th} layer. Expressing the wave numbers in this way allows experimentally observed loss factors to be used for the sediment layers (see Table 1). In the water column, sound absorption due to chemical relaxation and viscosity are included.[7]

2.1 Arrays of towers

Due to linear superposition, the pressure field produced by an array of pulsating wind turbine towers may be modeled by adding the individual contributions from each tower. If the towers are identical then P_{tower} must be calculated only once, and the total field is found simply by moving the coordinate system origin to each tower location, interpolating the pressure field onto a fixed grid of observation points $\mathbf{r}$, and summing, i.e.,

$$P_{array} = \sum_j e^{i\phi_j} P_{tower}(\omega, \mathbf{r} - \mathbf{r}_j) \tag{2}$$

where $\mathbf{r}_j = (x_j, y_j, z)$ and (x_j, y_j) is the location of the j^{th} tower, and ϕ_j is the pulsation phase of the j^{th} tower. For incoherent pulsation ϕ_j is a random number chosen from some distribution and is unique to the j^{th} tower, while for coherent pulsation the phase factor ϕ_j is constant.

It must be emphasized that the aforementioned summation represents a most unlikely worst-case scenario. In particular, it is based on the assumption that each tower is radiating at the same frequency, which is certainly not the case. For a variety of reasons (nonuniform wind speed across the farm, random variations in the gear noise, etc.), the sound will not be as tonal as is shown in Fig. 3 (Sec. 2.3) for individual towers. Suppose, for example, that the average fundamental frequency is 200 Hz. At distances far from the farm, such that in terms of spreading loss the towers appear to be equidistant from the hydrophone, the noise at the hydrophone might hypothetically cover a frequency band extending from 150 Hz to 250 Hz. Then, for example, suppose there are 100 towers in the farm, with 10 radiating at 155 Hz with 10 Hz bandwidth, 10 at 165 Hz with 10 Hz bandwidth, etc., up to the last 10 radiating at 245 Hz with 10 Hz bandwidth. The energies in these 10 frequency bands do not add to one another, so the spectrum level would be reduced by $10\log_{10} 10 = 10$ dB from the value calculated on the basis of Eq. (2).

3 Simulations parameters

Simulation parameters for the sediment types, source characteristics, seabed bathymetry and ambient noise considered in this report were taken from the literature and are outlined below.

3.1 Seabed parameters

Three types of seabed were investigated: silt, sand and basalt. By far, at least along the continental shelf off the east coast of the U.S., sand is the most common bottom composition. Silt and basalt are included as extremes insofar as silt is very soft and introduces very large bottom losses, whereas basalt is very hard, thus very reflective, and the bottom losses are very small. Bottom losses for sand lie in between these extremes.

The properties of each bottom type are given in Table 1 and were taken from Table 1.3 in Ref. 4. The three canonical seabed types were chosen to provide a wide range of impedance contrasts and loss factors in the simulations.

Bottom type	ρ kg/m^3	c_l m/s	c_t m/s	α_l dB/λ	α_t dB/λ
Silt	1.7	1575	$80\xi^{0.3}$	1.0	1.5
Sand	1.9	1650	$110\xi^{0.3}$	0.8	2.5
Basalt	2.7	5250	2500	0.1	0.2

Table 1: Sediment properties (taken from Table 1.3 in Ref. 4). The quantity ξ is depth referenced to the water-sediment interface. The labels dB/λ mean decibels per wavelength.

3.2 Source parameters and model validation

Source parameters were motivated by those measured at the Utgrunden wind farm off the coast of Sweden in 2002 and 2003.[1] In the Utgrunden study accelerometers were mounted on the support towers of the wind turbine at distances of 8 and 25 m above the water line and pressure in the water column was simultaneously measured at multiple distances from the wind farm. The accelerometer and hydrophone signals at frequencies below 2000 Hz are shown in Fig. 16 of Ref. 1. In this case only one wind turbine was operating and the pressure was measured at a range of 83 m from the support structure and at a depth of approximately 9 m. The water column depth in this case was approximately 10 m. The data show that except near frequencies of gear box resonances, the radial acceleration of the support structure and the measured pressure levels are approximately constant with frequency. To simplify matters we will assume in this example that the radial acceleration has a nominal amplitude of 2 mm/s^2 across the entire frequency band, as reported in the Utgrunden study. The diameter of the tower was assumed to be 4 m, and the tower was assumed to be constructed of steel with wall thickness 5 cm.

Measurements of the axial vibration pattern (along the length of the towers) were not available, and a suitable model could not be found for the case of a partially submerged cylindrical shell embedded in sediment. Therefore three simplified models for the axial variation of the tower vibration amplitude were investigated:

1. Uniform pulsation - In this case the entire length of the tower pulsates radially in phase at an amplitude of 2 mm/s^2. This case corresponds to an infinite phase speed for the elastic waves travelling down the tower.
2. Bending wave motion - In this case bending waves travel down the tower at the bending wave speed. The surface acceleration of the portions of the tower in the water column and sediment is decreased from the nominal value measured in air (2 mm/s^2) by a frequency dependent factor which was derived by considering the dynamics of a partially-loaded thin elastic plate. The surface acceleration of each tower segment is shown in Fig. 2.
3. Poisson effect - In this case vibrations travel down the tower with the longitudinal wave speed of steel and axial accelerations are transformed into to radial motion and coupled to the water column and sediment via the Poisson effect. Poisson's ratio for steel is approximately 0.3.[3]

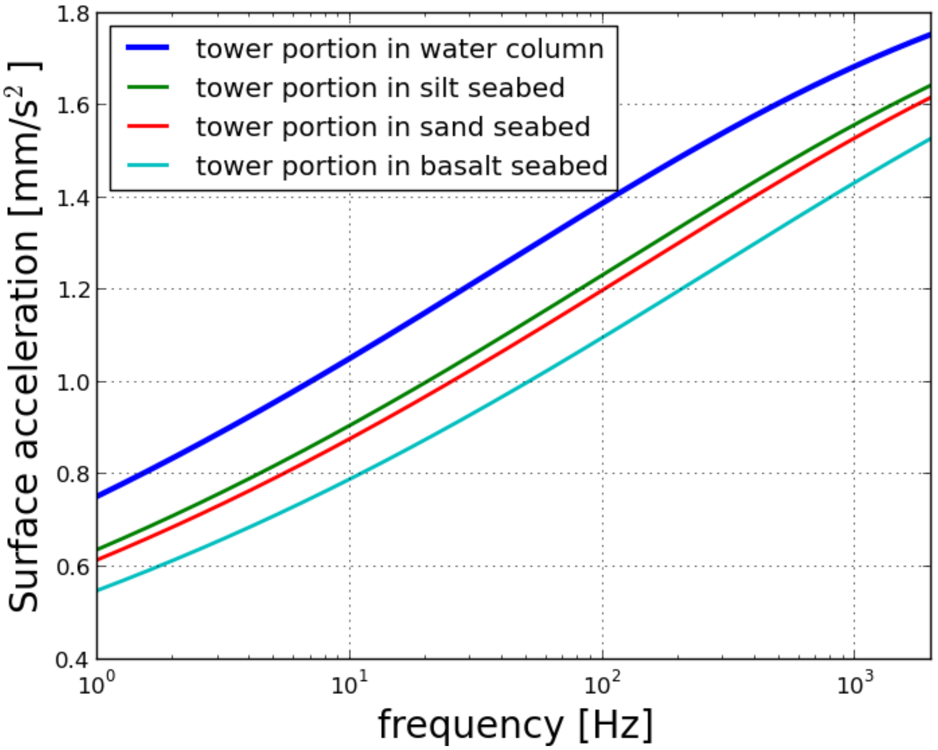


Figure 2: Surface acceleration of the portions of the tower in the water column and silt, sand, and basalt sediment for bending wave motion.

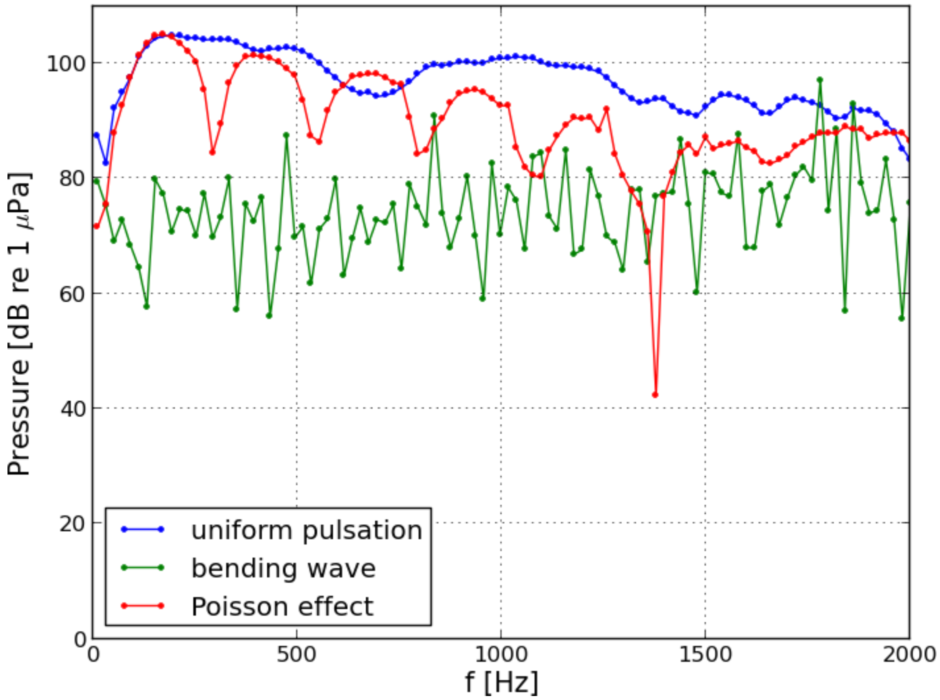


Figure 3: Comparison of three different source models with source levels comparable to those reported in Ref. 1. Simulated pressures received at a range of 83 m and depth of 9 m in a 10 m deep water column over a silt seabed. It was assumed that the tower extended 10 m into the seabed. The maximum surface acceleration of the tower was 2 mm/s^2. Average measured pressures reported in Ref. 1 were approximately 0.01 Pa, or 80 dB (re 1 μPa).

In order to validate the model, the pressure measurements reported in Fig. 16 of Ref. 1 were compared with the source model for each of the axial vibration patterns described above. In the case of the bending wave pattern the sediment was assumed to be sand. As shown in Figs. 15 and 16 of Ref. 1, the measured received pressure at a range of 83 m and depth of 9 m was approximately 0.01 pascals, or 80 dB (re 1 μPa). The simulated pressures, presented in Fig. 3 for both uniform pulsation and the Poisson effect axial shading are about 90 to 100 dB on average, or 10 to 20 dB higher than the measured pressures. In the case of the bending wave, axial shading the simulated pressure is about 80 dB on average but varies greatly with frequency. In order to provide a conservative estimate of expected noise levels and to avoid any sampling bias issues in the remainder of this report the tower will be assumed to pulsate uniformly.

3.3 Bathymetry parameters

The bathymetries considered in this report were taken from four potential mid-Atlantic sites for off-shore wind farms,[9] which are represented by the red dots in Fig. 4. Bathymetry profiles were obtained from the ETOPO1 global relief model.[8] Note that the nominal water column depth at all of the sites is approximately 25 m. The longitude, latitude and water depth of each site are given in Table 2.

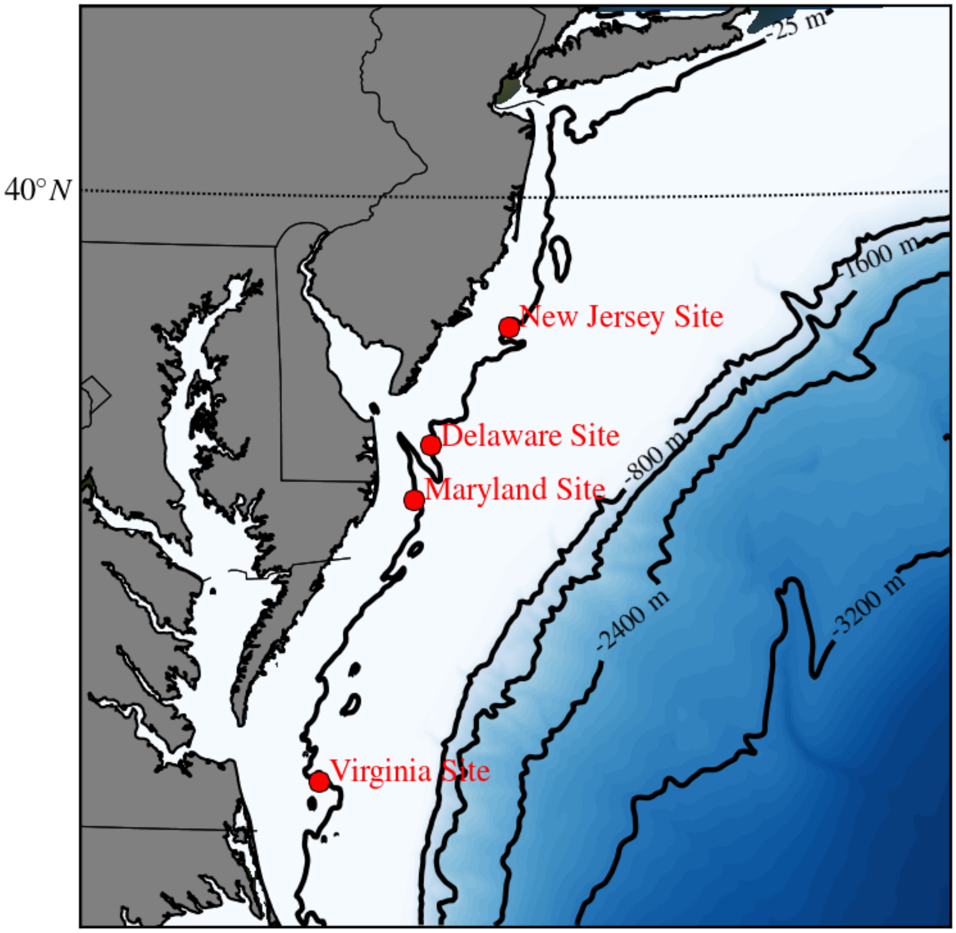


Figure 4: Map of four potential mid-Atlantic sites for off-shore wind farms.[9]

Site Name	Longitude degrees	Latitude degrees	Water Depth m
New Jersey	-74.14	39.29	25.0
Delaware	-74.68	38.65	24.6
Maryland	-74.80	38.35	25.8
Virginia	-75.42	36.82	25.2

Table 2: Data for four potential mid-Atlantic sites for off-shore wind farms.[9]

Bathymetric projections due east and due south were considered for each site and are shown in Fig. 5. Note that the profiles for the Delaware and Maryland sites are similar. We will therefore only consider the New Jersey, Maryland and Virginia sites in the remainder of the report.

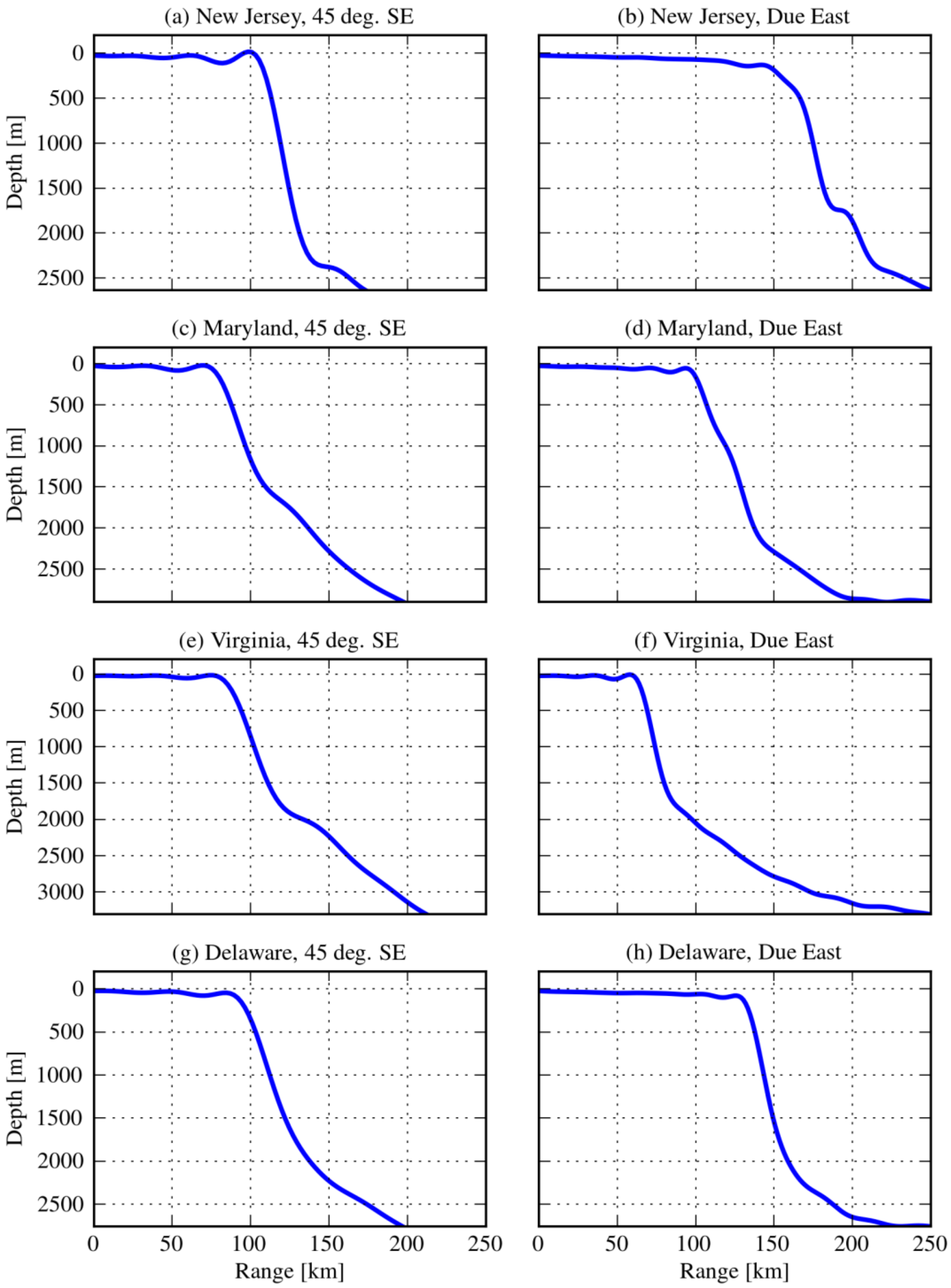


Figure 5: Bathymetry profiles in the southeastern (left column) and eastern (right column) directions from the four mid-Atlantic sites. Bathymetric data were obtained from the ETOPO1 dataset.[8]

4 Simulation results

Simulation results obtained with the source and PE models outlined in Sec. 2 for a cylindrical wind turbine tower with diameter of 4 m are now presented. In order to provide a conservative estimate of the potential noise impact, the nominal uniform surface acceleration was assumed to be 5 mm/s^2 across the entire frequency band below 2000 Hz. Examination of the radial accelerometer measurements presented in Figs. 16 and 17 of Ref. 1 shows that 5 mm/s^2 is approximately the correct value for some of the minor gearbox resonances (e.g., those between 94 and 157 Hz). However, the measured surface acceleration at some of the higher resonances (such as at 178 Hz) are higher, while the average surface acceleration below 2000 Hz is lower.

4.1 Range independent simulations

In Presented in this section are simulations of the sound field generated by a single tower. The water depth at each of the potential mid-Atlantic off-shore wind farm sites described in Sec. 3.3 is approximately 25 m, and therefore 25 m was taken as the canonical water column depth for the source model. Additionally, it was assumed that the tower is embedded 25 m into the seabed. The analysis in the remainder of the report is limited to eight logarithmically-spaced frequencies between 20 and 2000 Hz (i.e., 20, 38, 74, 143, 277, 536, 1035, and 2000 Hz).

Figures 6 – 13 show the sound pressure level (expressed in dB re 1 μPa) at each of the eight frequencies. The sound field due to the portion of the tower in the water column is shown in the first column of each figure, the sound field due to the portion of the tower in the seabed is shown in second column of each figure, and the third column is the total sound field (sum of the portions of the tower in the water column and seabed). The first, second, and third rows of each figure show results for silt, sand, and basalt seabeds, respectively. The horizontal dashed white line represents the location of the interface between the water and the ocean bottom at a depth of 25 m (water column from 0 to 25 m depth, and seabed at depths greater than 25 m).

Note that in all cases the pressure is zero at the surface due to the pressure release condition there. For all seabed types and at all frequencies there is transmission of sound from the water column into the seabed and from the seabed into the water column [evident in the first two columns of Figs. 6 – 13]. In Figs. 6 and 7 for 20 and 38 Hz, respectively, there is very little delineation between the water column and the seabed because these two frequencies are below the cutoff frequency of the waveguide formed by the air, water column and seabed. Energy below the cutoff frequency does not propagate and more easily leaks into the sediment. At frequencies greater than 74 Hz (Figs. 8–13) we see qualitatively different behavior, with a contrast between the water and seabed layers which sharpens with increasing frequency. This is because the acoustic energy is trapped in the layer in which it is generated and therefore propagates. Also notice that near the source (at small ranges) the sound pressures are greater in the seabed. This is because the impedance of the seabed (ρc) is greater than the impedance in the water column and therefore the uniformly pulsating tower produces higher pressures here for a given source strength. This effect is especially apparent for the basalt seabed examples [parts (g)-(i)], in which case the impedance contrast is greatest. However, the higher losses in the seabed layers cause the pressure fields to decay much more rapidly with distance in comparison with the sound field in the water column.

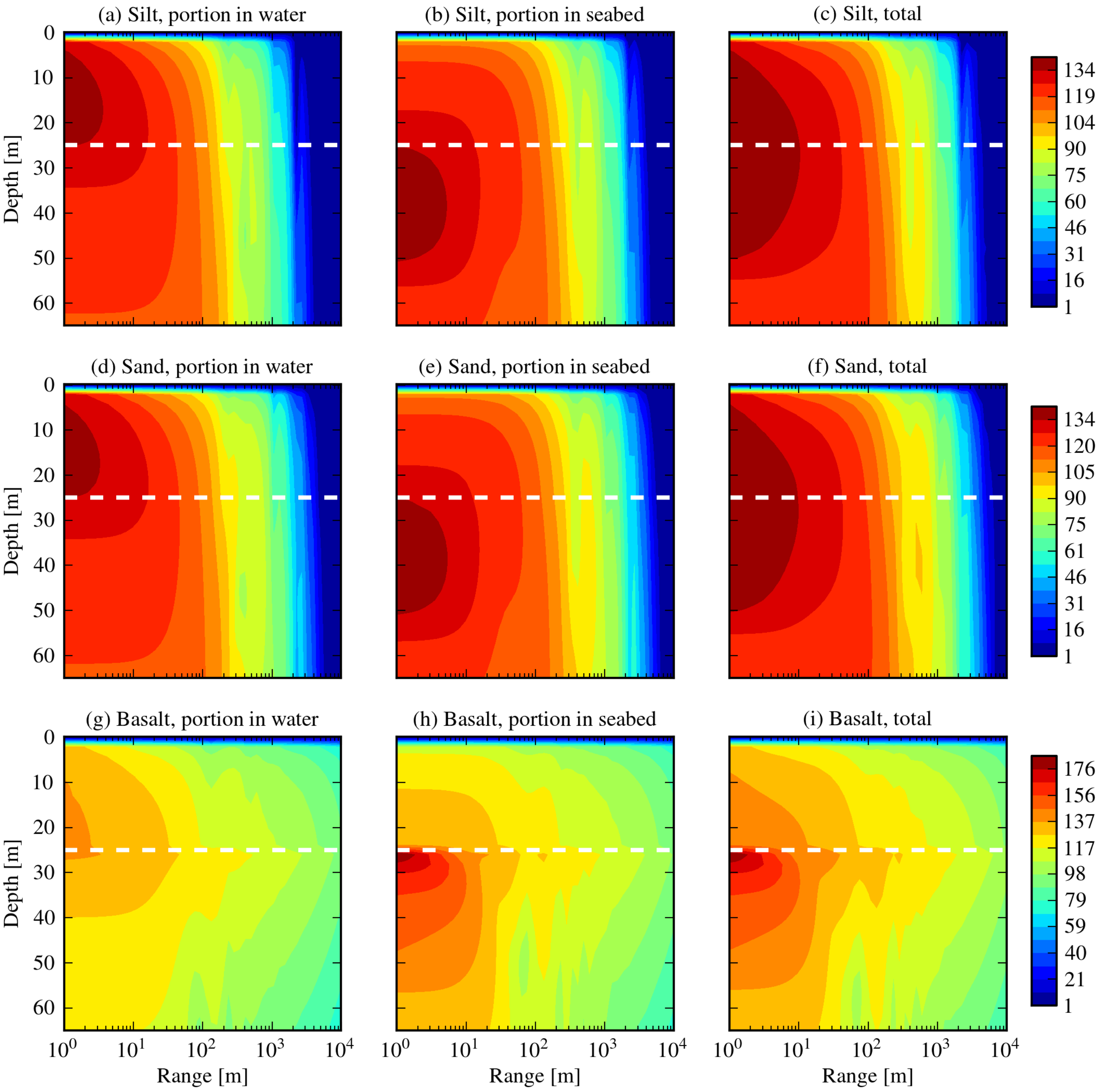


Figure 6: Pressure field (dB re 1 μPa) at 20 Hz.

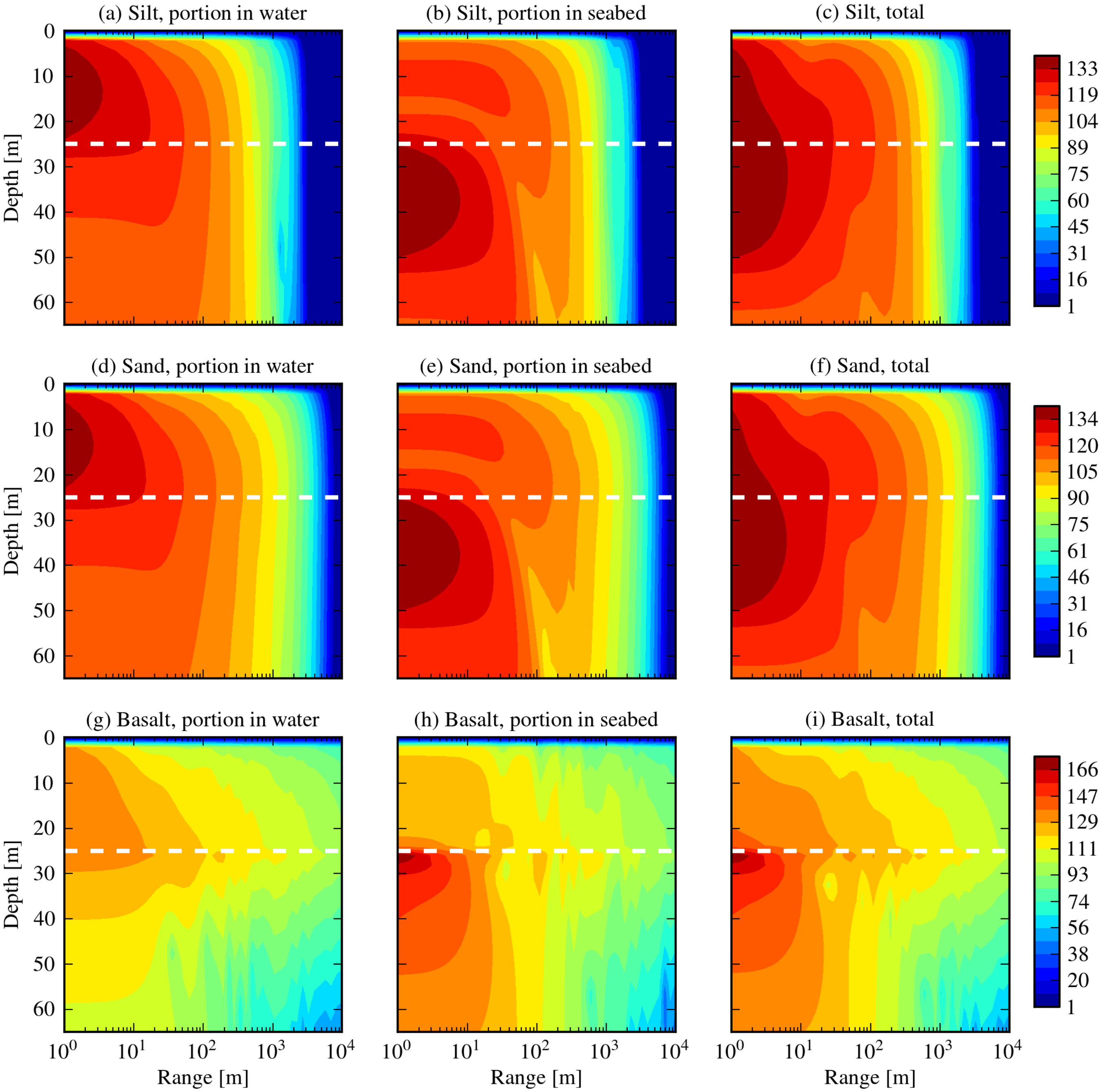


Figure 7: Pressure field (dB re 1 μPa) at 38 Hz.

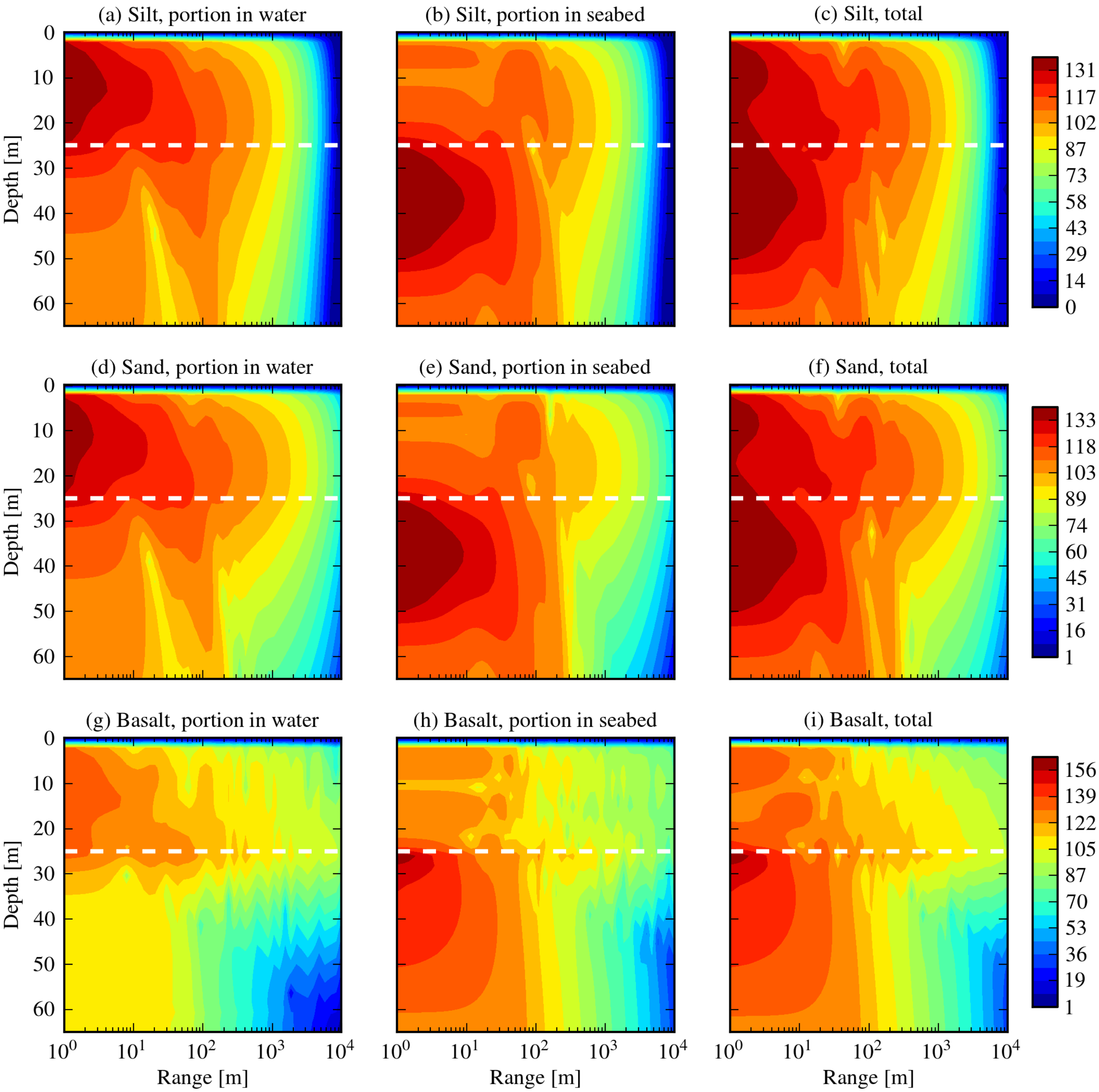


Figure 8: Pressure field (dB re 1 μPa) at 74 Hz.

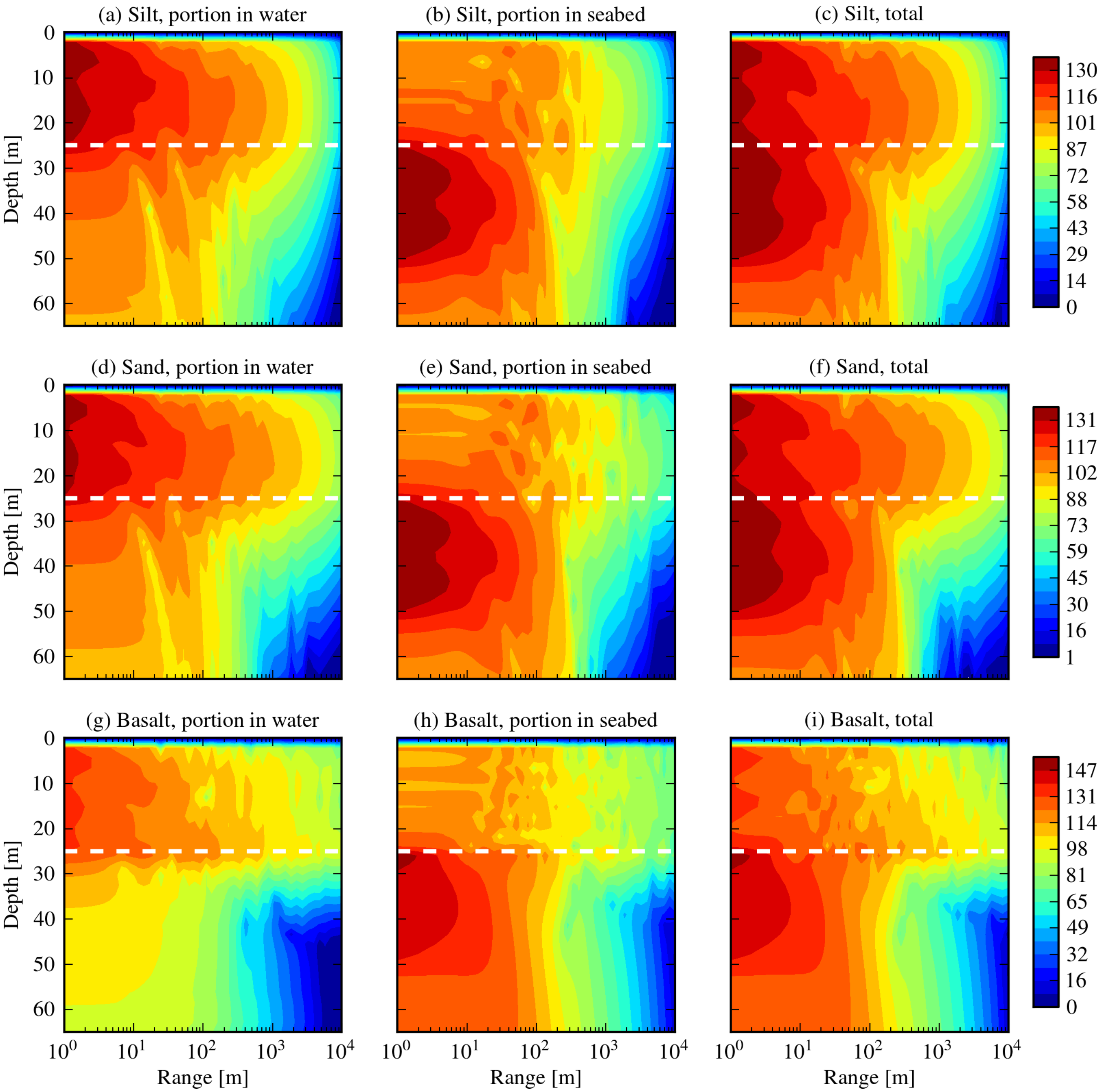


Figure 9: Pressure field (dB re 1 μPa) at 143 Hz.

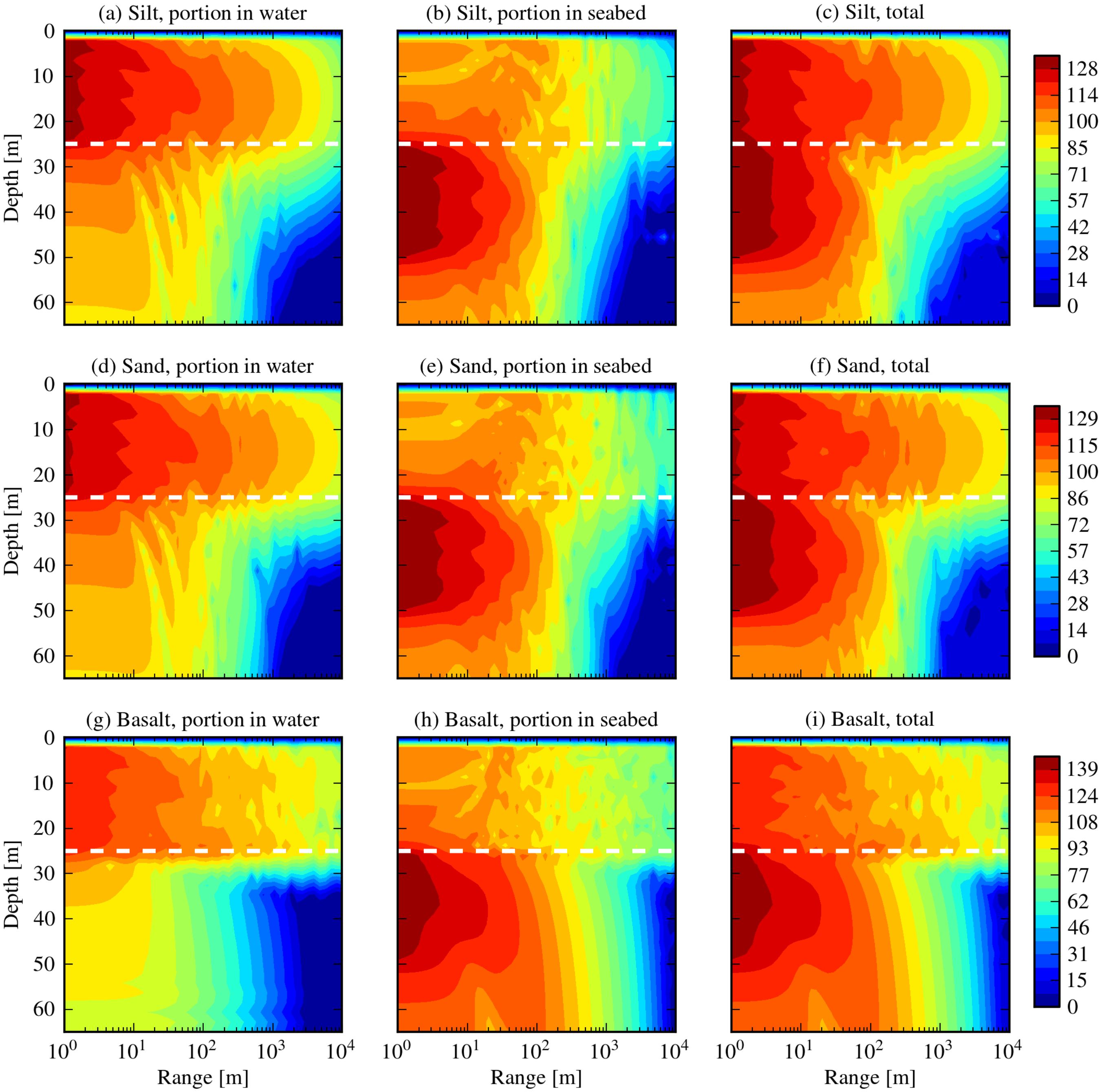


Figure 10: Pressure field (dB re 1 μPa) at 277 Hz.

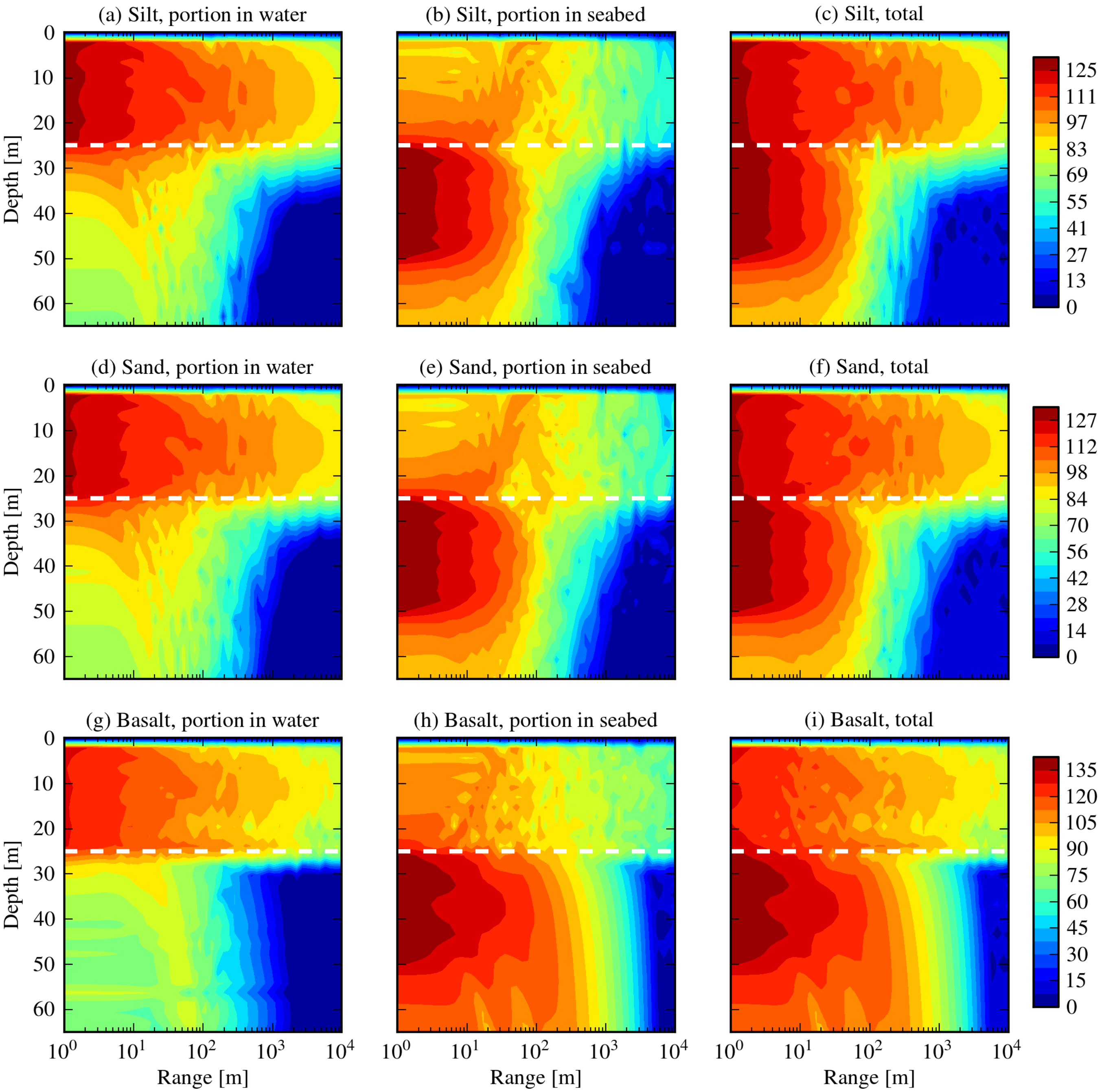


Figure 11: Pressure field (dB re 1 μPa) at 536 Hz.

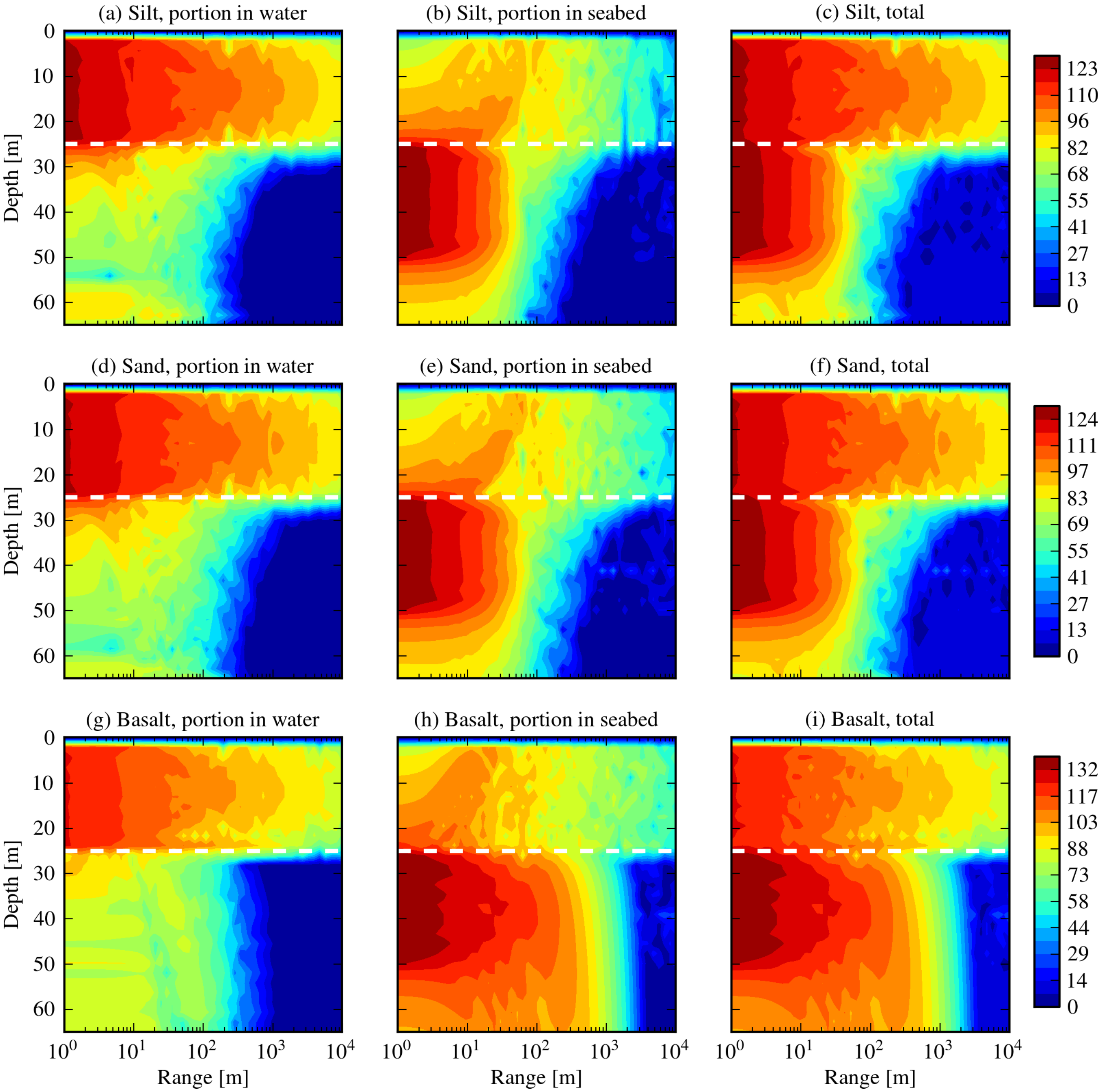


Figure 12: Pressure field (dB re 1 μPa) at 1035 Hz.

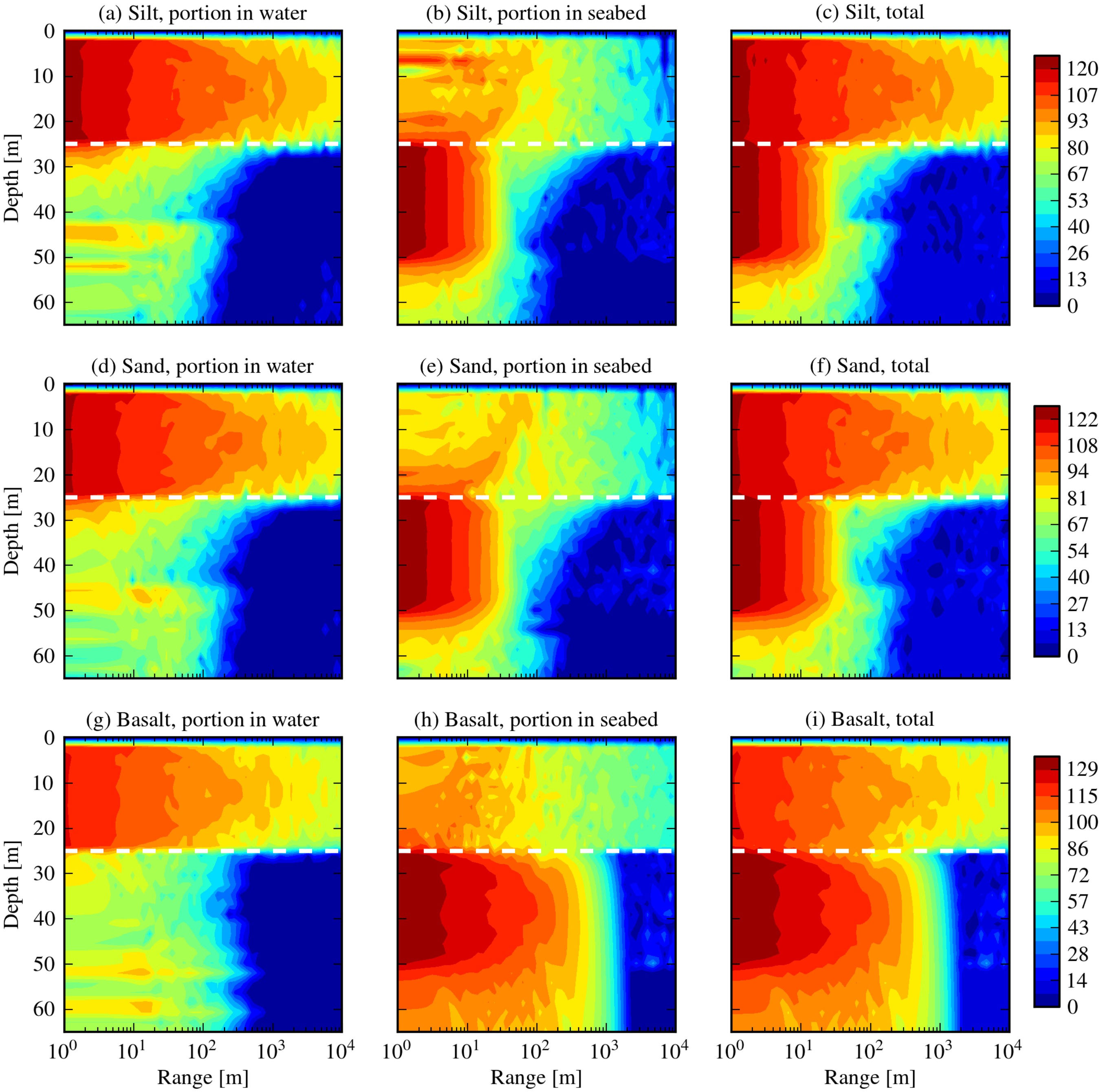


Figure 13: Pressure field (dB re 1 μPa) at 2000 Hz.

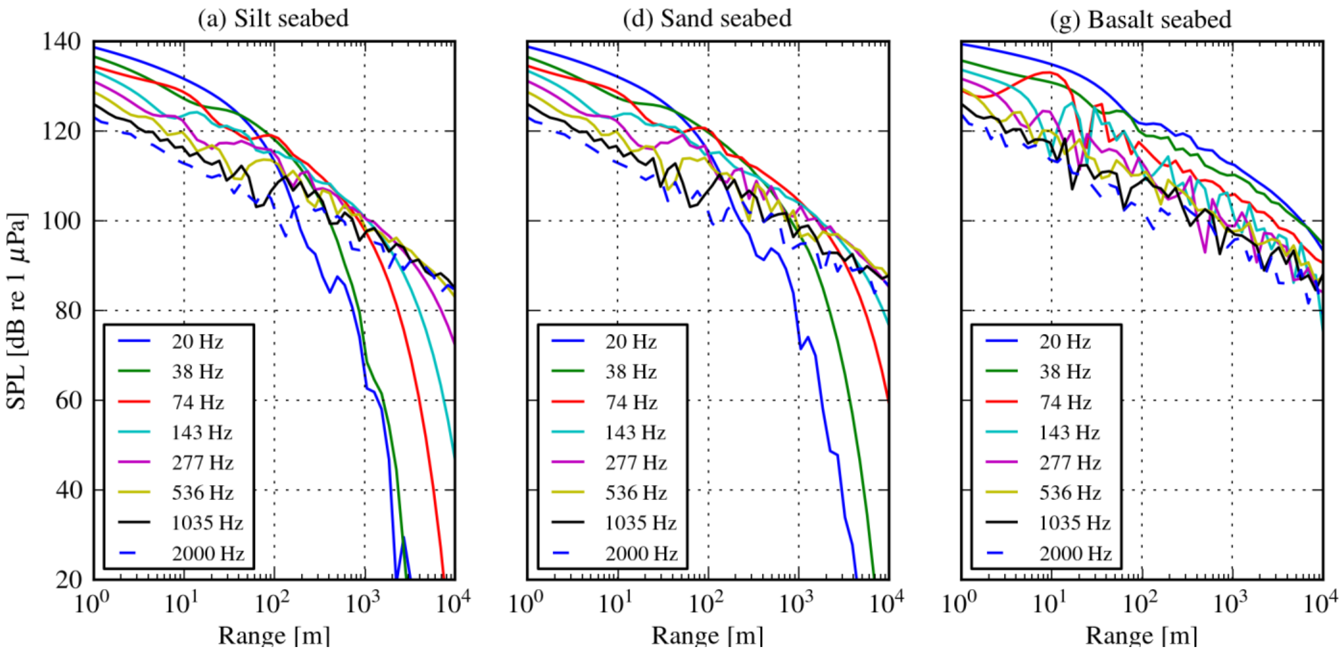


Figure 14: Pressure field (dB re 1 μPa) at a depth of z = 12.5 m for eight frequencies between 20 and 2000 Hz for silt, sand, and basalt seabeds.

Figure 14 shows the sound pressure level in the water column at a depth of 12.5 m (half the water column depth) at each frequency. Note that in all cases the pressure level falls off faster than 10 dB per decade of increased distance.

4.2 Arrays of towers

Figure 15 shows the pressure field given by Eq. (2) with range at a depth of z = 12.5 m for (a) a single turbine tower, (b) a 5x5 array of 25 towers spaced 1 km apart, (c) an 11x11 array of 121 pulsating towers (with the same 1 km spacing). In all cases the frequency is 143 Hz, and the seabed composition is sand. The black dots in the top row of Fig. 15 indicate the locations of the towers. The bottom row of figures shows a slice through the sound field at a depth of 12.5 m. It is apparent that the sound field close to the center of the array is similar to the sound field from a single tower. However, at ranges of more than the inter-tower spacing distance the total sound field follows a $10\log_{10} N$ law, which is what is expected for an ensemble of incoherent noise sources. Figure 16 shows the expected sound pressure levels at distances ranging from 500 m to 10 km from an array of N incoherently pulsating towers, assuming that the pressure scales as $10\log_{10} N$, for N ranging from 1 to 200 towers for each of the eight frequencies between 20 and 2000 Hz. In the remainder of the report we therefore simulate the noise from a single tower. Noise estimates for an array of N towers may then be obtained by adding $10\log_{10} N$ decibels to the noise estimates for a single tower. Again, it is emphasized that this addition rule is based on the assumption that all N towers are radiating at the same frequencies and therefore represents a worst-case scenario.

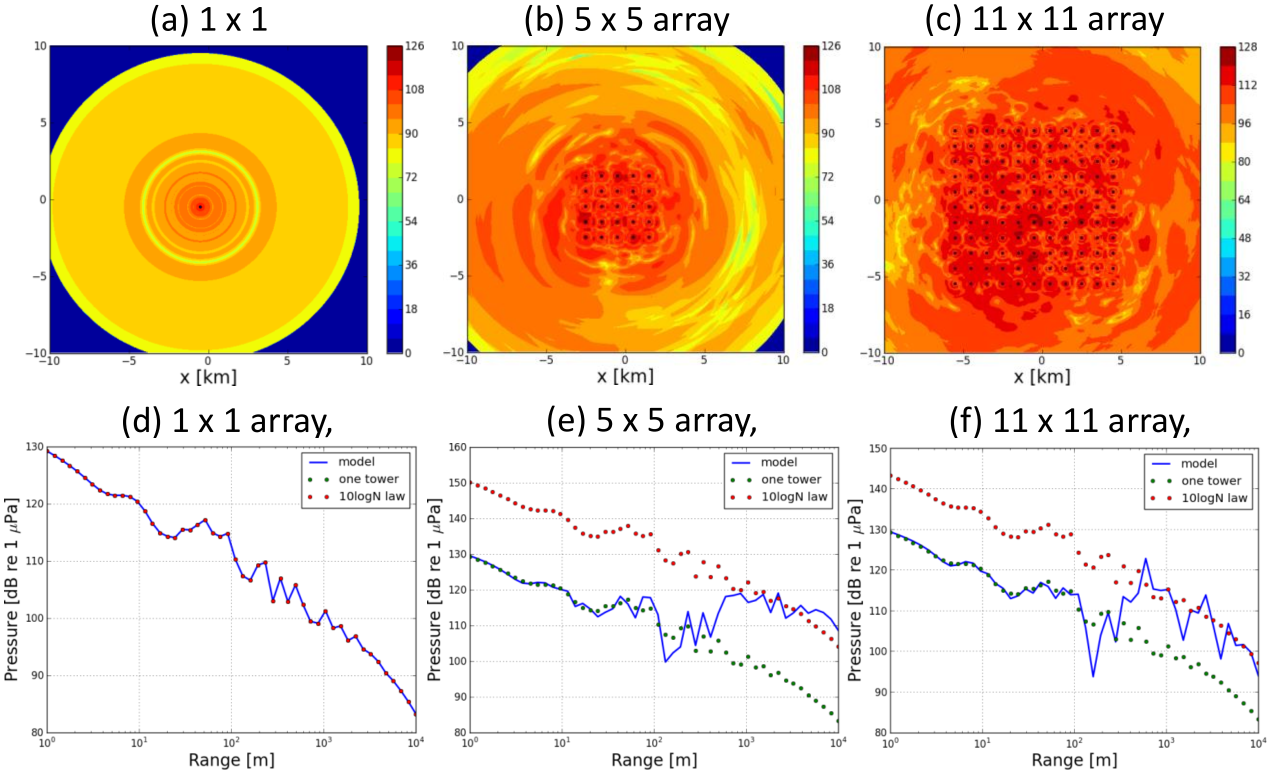


Figure 15: Pressure field (dB re 1 μPa) at a depth of z = 12.5 m and frequency of 316 Hz for a single tower, a 5x5 array of 25 and an 11x11 array of 121 towers. The spacing between towers was 1 km.

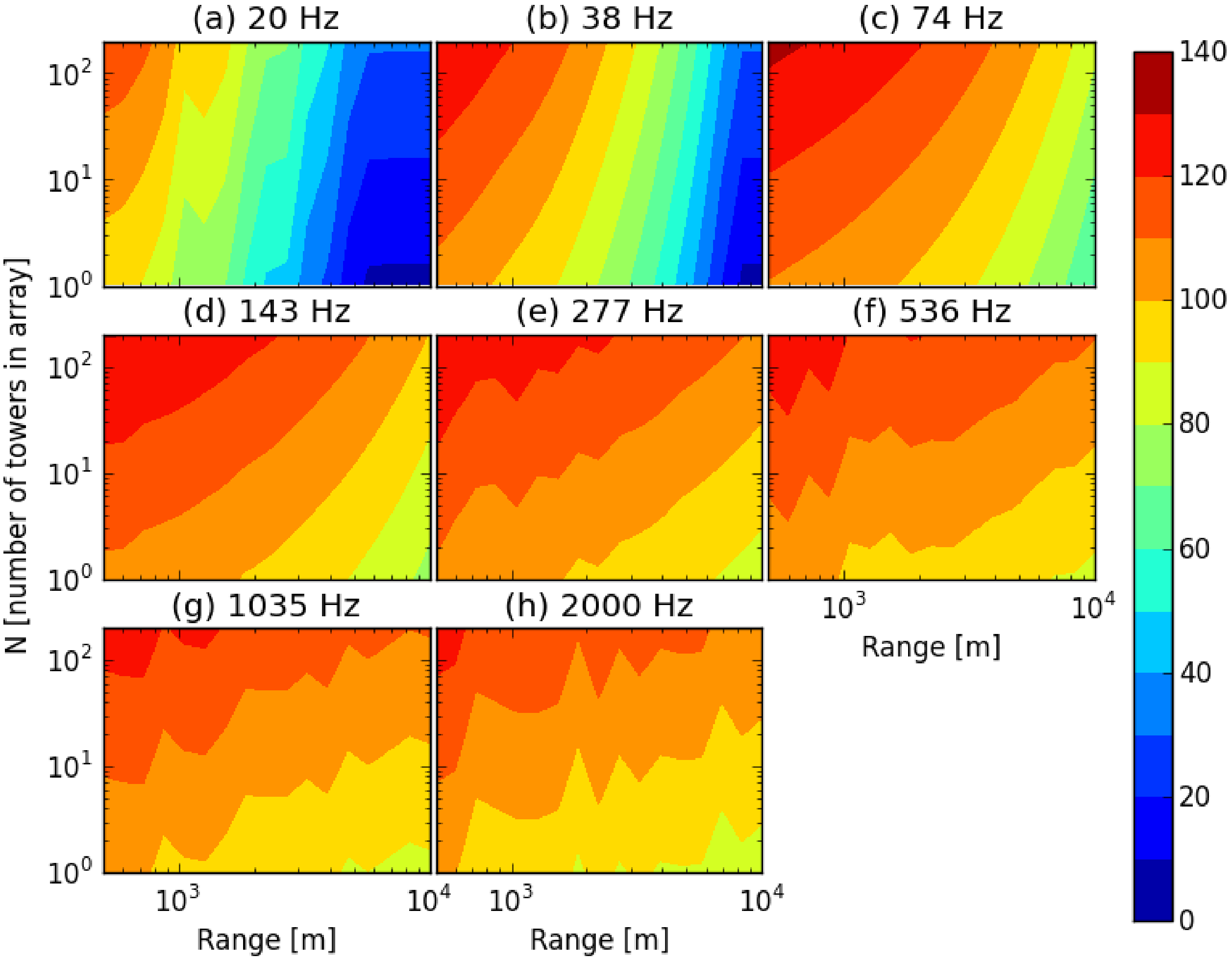


Figure 16: Pressure (dB re 1 μPa) at a depth of 12.5 m for arrays of *N* incoherently pulsating towers at distances ranging from 500 m to 10 km from the center of the array.

4.3 Range dependence

To simulate sound propagation through range-dependent environments the simulated sound field at a range of 10 km was coupled to a version of RAM modified to account for interaction with the seabed[5] and propagated to a range of 300 km over the bathymetries shown in Fig. 5, using a depth-dependent, but range independent, sound speed profile. The sound speed profile considered here is the idealized Munk profile, which is shown in Fig. 17. Note that the minimum sound speed occurs at a depth of 1000 m.

In Figs. 18–20 we have paired the New Jersey site bathymetry profiles with the silt seabed, the Maryland site profiles with the sand seabed, and the Virginia site profiles with the basalt seabed. While the seabeds at each of these sites are predominantly sand, we have artificially chosen silt and basalt only for illustrative purposes. We have selected frequencies of 20, 277, and 1035 Hz to demonstrate sound propagation though each bathymetry and seabed combination. The top row of each figure shows the sound field along the east bathymetric projection, and the bottom row of each figure shows the sound field along a southeastern projection.

Simulations for the New Jersey site with a silt seabed are show in Fig. 18. At 20 Hz [parts (a) and (b)] the model simulations show that the sound attenuates completely by a range of 10 km [see Fig. 6]. The farthest propagation occurs at 1035 Hz, for which the sound field is non-zero up to a range of about 100 km from the tower. Simulations for the Maryland site with a sand seabed are shown in Fig. 19. Here we see similar results at 20 Hz, for which the sound field has attenuated completely at 10 km. At frequencies of 277 Hz and 1035 Hz for the east profile [Fig.19(c),(e)] the sound field couples into the deep ocean and refracts around a depth of 1000 m where the sound speed is minimum. This is commonly called the sound fixing and ranging, or SOFAR, channel. Figure 20 shows simulations for the Virginia site with a basalt seabed. In this case we do see some propagation at 20 Hz [parts (a) and (b)] but the sound does not couple into the deep ocean and is blocked at a range of 100 km. Propagation in the southern direction [parts (b),(d) and (f)] is blocked by a shallow region starting at 150 km, but in the eastern direction sound does couple into the SOFAR channel at frequencies of 277 [part (c)] and 1035 Hz [part (e)].

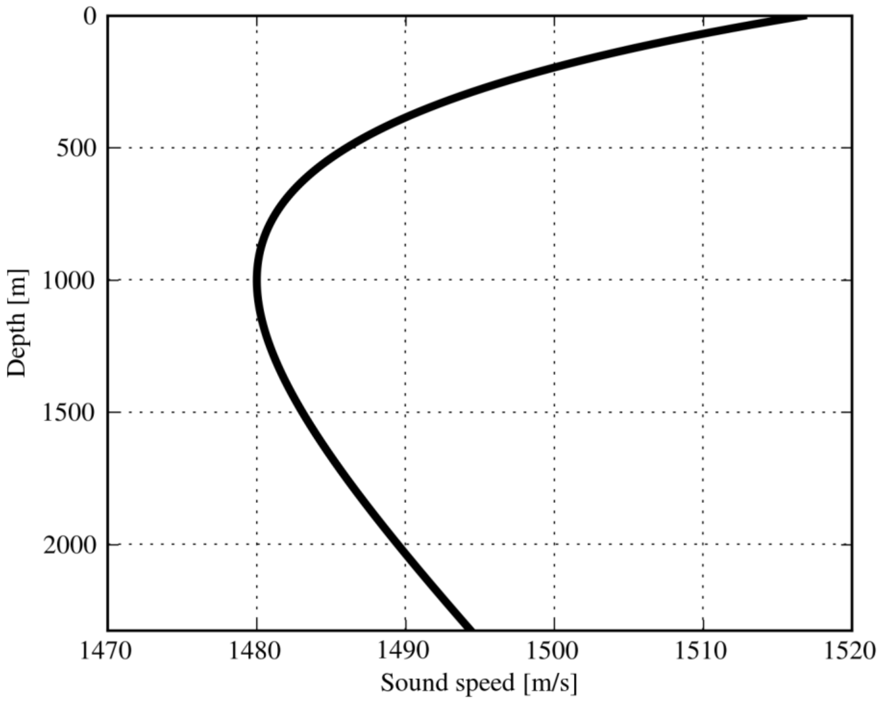


Figure 17: Munk sound speed profile

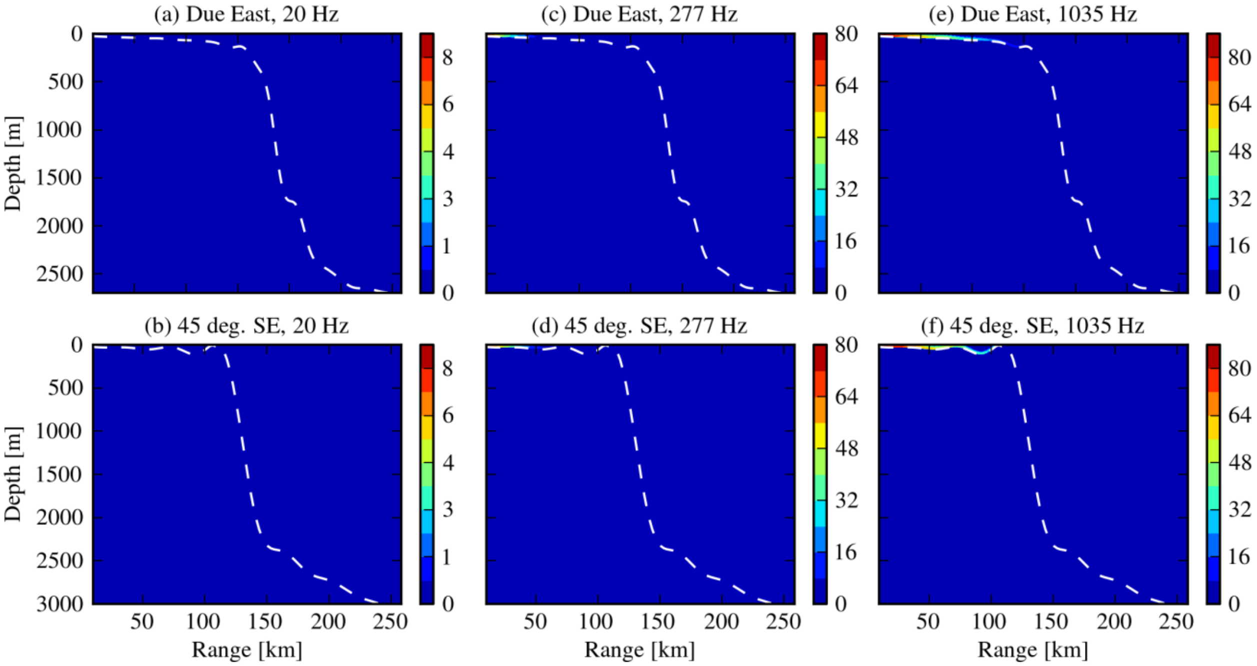


Figure 18: Pressure fields (dB re 1 μPa) for a silt seabed. New Jersey site.

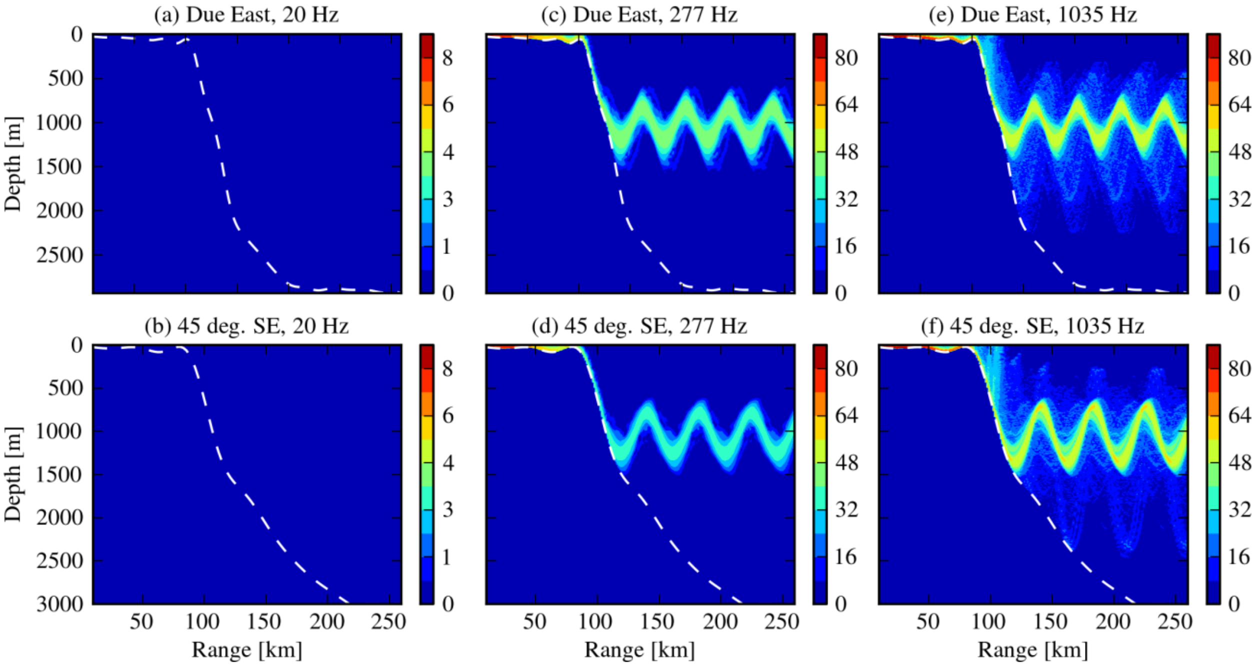


Figure 19: Pressure fields (dB re 1 μPa) for a sand seabed. Maryland site.

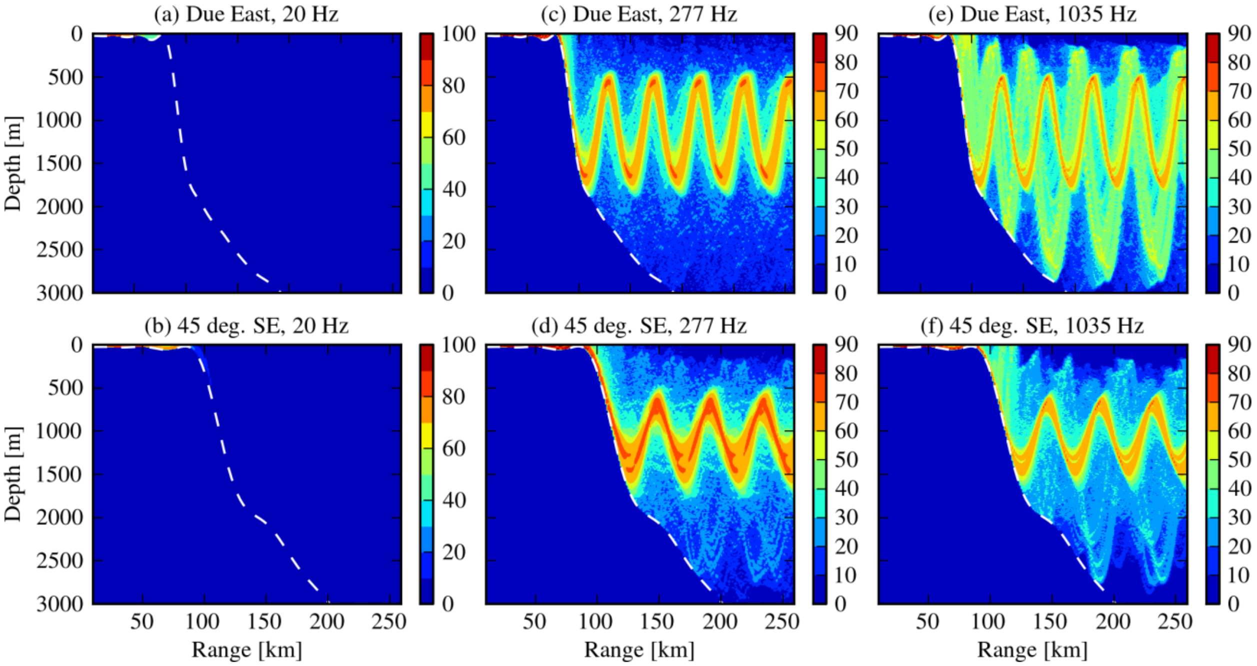


Figure 20: Pressure fields (dB re 1 μPa) for a basalt seabed. Virginia site.

5 Bibliography

[1] Ingemansson Technology AB, “Utgrunden off-shore wind farm - measurements of underwater noise”, Technical Report, Ingemansson Technology AB (2003).

[2] T. A. Hay, Yu. A. Ilinskii, E. A. Zabolotskaya, and M. F. Hamilton, “Model for underwater noise radiated by submerged wind turbine towers,” Proceedings of Meetings on Acoustics **19**, 070038 (2013).

[3] P. G. Reinhall and P. H. Dahl, “Underwater mach wave radiation from impact pile driving: Theory and observation”, The Journal of the Acoustical Society of America **130**, 1209–1216 (2011).

[4] F. B. Jensen, W. A. Kuperman, M. B. Porter, and H. Schmidt, *Computational Ocean Acoustics*, 2nd edition (Springer-Verlag, New York, NY (USA)) (2011).

[5] M. D. Collins, “A split-step Padé solution for the parabolic equation method”, J. Acoust. Soc. Am. **93**, 1736–1742 (1993).

[6] T. A. Hay, Yu. A. Ilinskii, E. A. Zabolotskaya, and M. F. Hamilton, “Model for bubble pulsation in liquid between parallel viscoelastic layers”, J. Acoust. Soc. Am. **132**, 124–137 (2012).

[7] D. T. Blackstock, *Fundamentals of Physical Acoustics*, Appendix B, 516–518 (Wiley, New York) (2000).

[8] C. Amante and B. W. Eakins, “ETOPO1 1 arc-minute global relief model: Procedures, data sources and analysis”, NOAA Technical Memorandum NESDIS NGDC-24, NOAA (2009).

[9] K. Barkoff, "Salazar, Chu announce major offshore wind initiatives", **http://http://www.doi.gov/news/pressreleases/Salazar-Chu-Announce-Major-Offshore-Wind-Initiatives.cfm** (2011), [Online; accessed 20-March-2013].

[10] W. H. Munk, "Sound channel in an exponentially stratified ocean, with application to SOFAR", J. Acoust. Soc. Am. **55**, 220–226 (1973).

Appendix D
Approval for Public Release Documents

RE: approval for public release of appendix sections C1.1 and C1.2

From Esayev, Viktoriya

To Hao Ling
Hahn, Michael

CC Silbergleid, Steven
Gutierrez, Kim
Hambleton, Susan

Michael,

Per your request I have reviewed the Appendix sections C1.1 and C1.2 for the University of Texas at Austin's project entitled "Assessment of Offshore Wind Farm Effects on Sea Surface, Subsurface, and Airborne Electronic Systems" for possible export control issues. In my opinion, Appendix sections C1.1 and C1.2 for the University of Texas at Austin's project entitled "Assessment of Offshore Wind Farm Effects on Sea Surface, Subsurface, and Airborne Electronic Systems" **doesn't** contain any "technical data" that is controlled and would require a license from Department of State to be released.

Please let me know if you have any more questions regarding this determination.

Thanks,

Viktoriya Esayev
Export Control Compliance Officer
National Renewable Energy Laboratory
Tel.: 303-275-4269
http://thesource.nrel.gov/foreign_nationals/export_control.html

From: Stubstad, John, Dr, OSD-ATL
Sent: Friday, May 24, 2013 10:01 AM
To: Harris, Paula CIV WHS-ESD; 'haoling2000@yahoo.com'
Subject: Re: SR CASE 13-S-1826 - 2006 AFRL wind farm measurement data - for public release

Paula

The three graphical plots were published by AFRL several years ago in a conference paper. That paper had been approved for release under the standard review process used by the AF.

Dr Ling's plots are exactly the same information. I suggested he submit them for review only out of an abundance of caution.

From your message it appears that was unnecessary.

DR John Stubstad.

Dr John Stubstad (SES)
Director, Space and Sensor Systems
Research Directorate
Office of the Assistant Secretary of Defense, Research and Engineering
4800 Mark Center Drive, Suite 17E08
Alexandria, VA 22350

From: "Harris, Paula CIV WHS-ESD" <Paula.harris@whs.mil>
To: "Stubstad, John, Dr, OSD-ATL" <John.Stubstad@osd.mil>; "'haoling2000@yahoo.com'" <haoling2000@yahoo.com>
Sent: Friday, May 24, 2013 9:34 AM
Subject: RE: SR CASE 13-S-1826 - 2006 AFRL wind farm measurement data - for public release

That is correct. Data approved for public release by Air Force program office and currently in public domain - no need to send to OSR for a security review.

Paula J. Harris
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