# High Frequency Radar Wind Turbine Interference
# Community Working Group Report

June, 2019

## A-Executive Summary

Land-based High Frequency (HF) Radars provide critically important observations of the coastal ocean that will be adversely affected by the spinning blades of utility-scale wind turbines. Pathways to mitigate the interference of turbines on HF radar observations exist for small number of turbines; however, a greatly increased pace of research is required to understand how to minimize the complex interference patterns that will be caused by the large arrays of turbines planned for the U.S. outer continental shelf. To support the U.S.'s operational and scientific needs, *HF radars must be able to collect high-quality measurements of the ocean's surface in and around areas with significant numbers of wind turbines*. This is a solvable problem, but given the rapid pace of wind energy development, immediate action is needed to ensure that HF radar wind turbine interference mitigation efforts keep pace with the planned build out of turbines.

A comprehensive mitigation strategy, with specific research objectives, is required to ensure that HF radars will be able to provide continuous observations in service of our national environmental intelligence needs:

1. In the near-term (0-6 months), expanded observations at existing wind farms and improved simulations of wind turbine interference are required.
2. In the mid-term (6 months to 2 years), initial mitigation methods should be developed and tested using historical datasets, simulations, and in situ observations from within the first major installation;
3. In the long term (2-5 years), a robust and coordinated in situ effort should be carried out to validate mitigation methods, test mitigation software for surface current products, and further mitigation development for advanced HF radar products.

This community working group report should be widely distributed to all interested parties.

**Document Outline:**

## B-Introduction

High Frequency (HF) radar is a critical component of our nation's efforts to observe and monitor the coastal ocean. These land-based, remote sensing systems are the only instruments capable of making both high spatial resolution and high temporal resolution observations of the movement of waters at the ocean's surface over the outer continental shelf. In the U.S., a distributed network of research scientists, in partnership with the U.S. Integrated Observing System (IOOS), have been operating HF radar systems for more than two decades. Data from the HF Radar Network is used by the U.S. Coast Guard and NOAA for search and rescue operations and spill response as well as by individual scientists on a daily basis.

However, the rapidly emerging offshore wind energy industry in the U.S. has the potential to degrade the performance of HF radar systems operating in the vicinity of wind turbines. A recently completed study (Trockel et al.2018) has documented the wind turbine interference (or "WTI") on HF radars and shown that the location and the magnitude of the interference can directly interfere with accurate measurements over broad areas of the radar's coverage. For small numbers of turbines, pathways to mitigate the interference exist. Yet, the offshore wind industry will soon outpace these simplified solutions as plans for large farms of turbines are moving towards installation. This near-future scenario greatly exceeds the scope of initial efforts and at present no operational solutions exist to mitigate the future interference.

Mitigating the interference of wind turbines on HF radar measurements is a solvable problem. With efforts to complete our understanding of the interference signal, and develop and test mitigation solutions, HF radars should be able to maintain their existing performance in planned wind turbine areas. An HF Radar Community Working Group was charged by IOOS (Appendix B) to examine the state of the science and develop comprehensive recommendations of the future actions required to fully mitigate any WTI effects on radar performance.

This document seeks to provide federal and state agencies, stakeholders, and researchers with a complete assessment of the state of knowledge regarding the interference of wind turbines on the observations collected by HF radars. This work provides a set of prescriptive recommendations of what activities or actions should be taken to ensure the effects of wind turbines on HF radar observations will be fully mitigated within the next 5 years. Both immediate and near-term actions, as well as longer term efforts over the coming years, are required to ensure the uninterrupted delivery of high quality observations by the National HF Radar Network.

*This document is organized as follows:* Background information on HF radars, the National HF Radar Network, and previous efforts to observe and simulate the effects of wind turbines on radar observations are described first, followed by a comprehensive discussion of the future actions and activities needed to achieve mitigation success. This discussion is then summarized into a timeline of required immediate (0-6 months), near-term (6 months to 2 years) and long-term (2-5 years) actions. Information on the working group and its charge are included at the end of the report.

## C-Background Information and Previous Mitigation Efforts

### *C.1 – Oceanographic High Frequency Radar and the Integrated Ocean Observing System*

Observing ocean surface currents is important for understanding the fundamental processes driving the coastal ocean. Wind-driven currents, freshwater outflows, tsunamis, and eddies are all critical aspects of the coastal ocean that can be well-observed by HF radar. Understanding surface currents is also important for meeting societal needs such as marine transportation, recreation, search and rescue operations, oil spill response, military activities, and monitoring marine protected areas. Many of these applications require real time monitoring of the coastal ocean that only HF radars are capable of providing, due to their unique combination of high spatial and high temporal resolution sampling.

The unique capabilities of HF radars has led to the incorporation of oceanographic radars as essential components of coastal ocean observing systems around the world. In the U.S., the

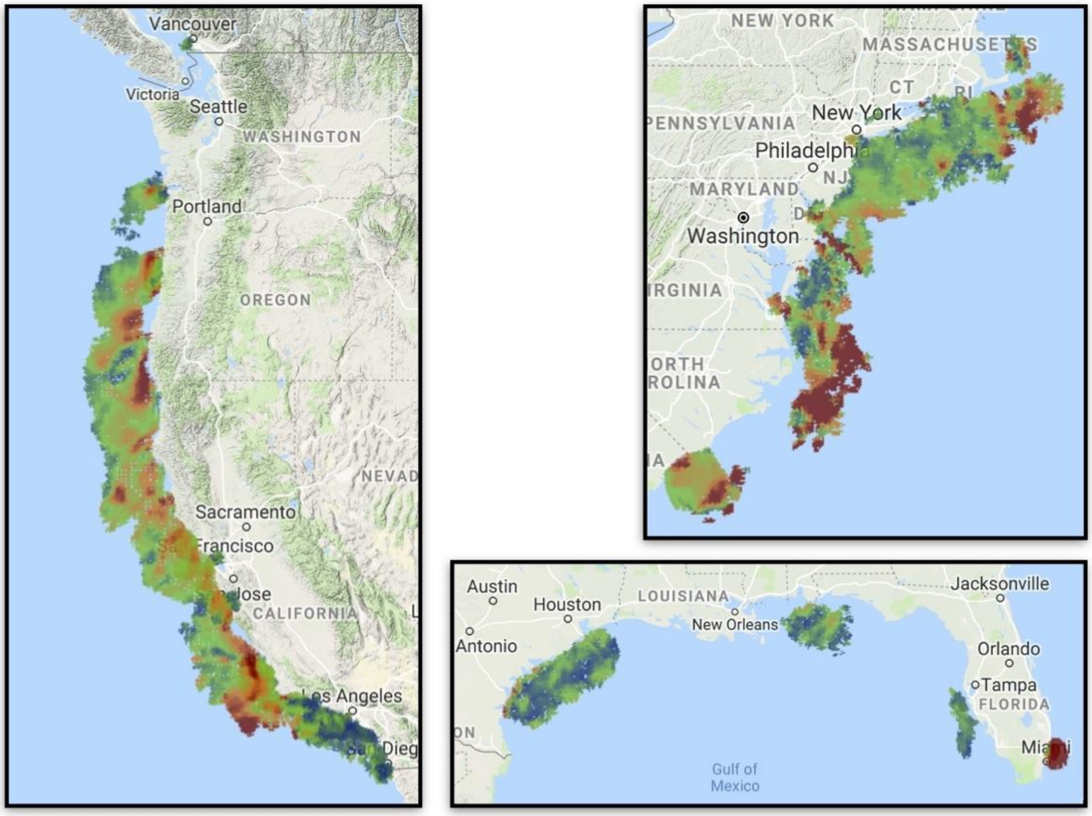


Figure 1: U.S. HF Radar long range., 6 km present day coverage along the West Coast, Gulf Coast, and East Coast (from the HF Radar Network)

IOOS program has supported the development of a network that currently comprises about 140 HF radar sites (Figure 1) along coastlines of the continental U.S., Hawaii, and seasonally in Alaska (Harlan et al. 2010). In addition to the applications mentioned above, ocean surface current maps support offshore oil and gas operations, offshore aquaculture, ecosystem-based management of living marine resources, design of marine protected areas, wastewater discharge, and monitoring hypoxia and harmful algal bloom (e.g. Shay et al., 2008; Harlan et al. 2011). While HF radar is an important scientific tool for coastal ocean dynamics, two applications in particular depend on it for operational needs. First, surface current data is provided to NOAA's Office of Response and Restoration, and state agencies like the California's Office of Spill Prevention and Response, which rely on this data for oil spill response. Second, surface current data products, including short term predictions , are used by the U.S. Coast Guard in their search and rescue activities.

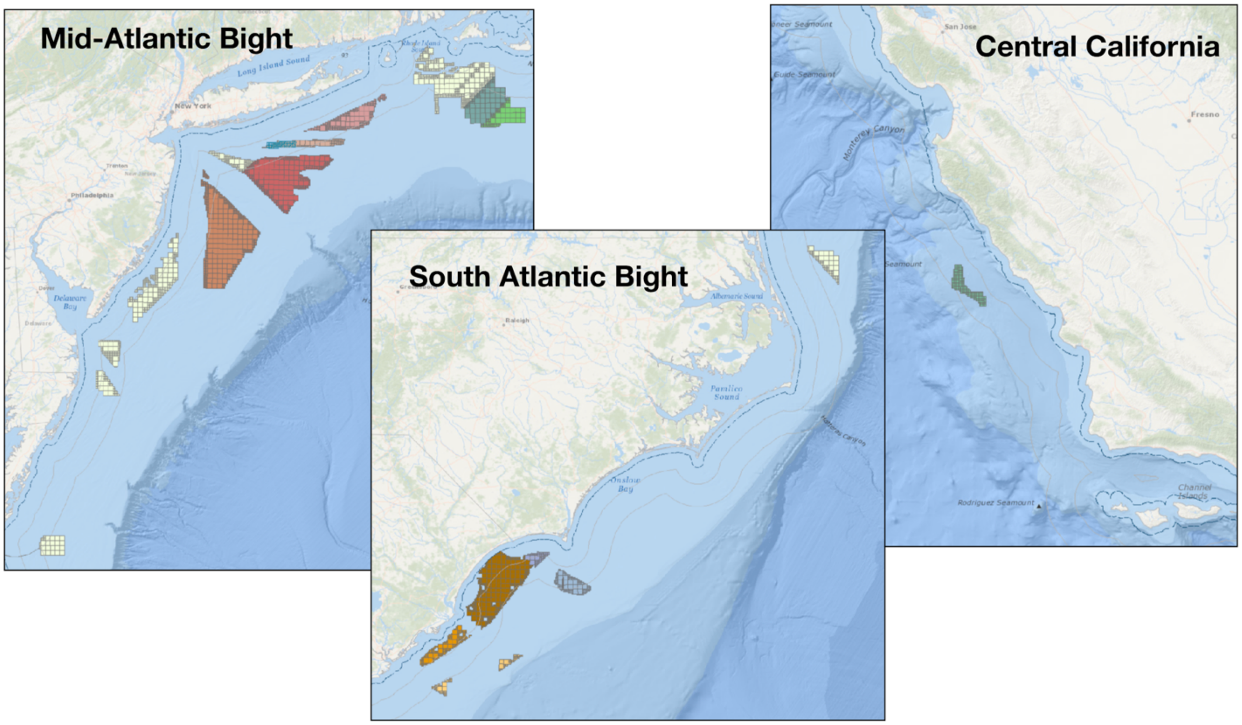
An ongoing campaign to close existing gaps in coverage has added large areas of the outer continental shelf in recent years. New data products are being developed that provide concurrent observations of ocean surface waves or surface winds and new situational awareness tools are being built and tested for vessel tracking and the early-warning detection of tsunamis. To ensure the viability of the network in the future it will be necessary to eliminate interference from offshore and nearshore wind turbines.

### *C.2 - Offshore Wind Energy in the U.S.*

Numerous offshore wind energy lease areas will be developed over the next decade in the U.S.. The first commercial offshore wind project, the Block Island Wind Farm, recently started operations in December 2016. This 30 megawatt (MW) project with five turbines is located within state waters off the coast of Rhode Island. Within the Mid-Atlantic Bight, the area between Cape Hatteras and Cape Cod, there are 15 active offshore wind lease areas in various stages of development with additional areas being proposed each year. Development in just the existing leased areas (see Figure 2) could amount to between 800 and 1,800 turbines installed between 15 to 50 NM offshore.

Offshore wind developments are also planned for the Southeast, West Coast, Great Lakes, and Hawaii. A number of lease areas already exist along the West Coast, where the timing of the diurnal wind cycle will soon make offshore wind economically viable, despite the deeper water depths. Towards this goal, the Department of Energy (DOE) is planning resource characterization campaigns along the West Coast in the coming year.

South of Martha's Vineyard, Massachusetts, construction in the Vineyard Wind lease area, will begin in the fall of 2019. The developer of this first major U.S. wind farm has proposed significantly larger turbines (9.5 MW) than those located in land based wind farms, increasing the impact of each turbine on radar observations. Additionally, their proposed array of 80-100



Mid-Atlantic Bight

South Atlantic Bight

Central California

Figure 2: Federal offshore wind energy lease areas or wind energy planning areas (from https://www.marinecadastre.gov).

turbines would result in significantly more interference signals than were seen in initial studies using the small Block Island wind farm.

Ironically, the offshore wind energy industry could greatly benefit from exactly the types of situational awareness observations that NOAA-IOOS produces through its support of the National HF Radar Network. At a minimum, surface current observations would provide key information on conditions in the lease areas for construction, operations, and maintenance activities. More advanced products such as detailed estimates of the surface waves and winds would improve planning as well as drive the data-rich, short-term wind power forecasts that the industry will require in the near future.

### *C.3 - Previous efforts to understand and mitigate wind turbine interference on HF radar*

It has long been known that wind turbines can have an impact on systems that employ transmitted radio signals (Sengupta, 1979). Prior to 2011, studies of wind turbine interference (WTI) focused primarily on aviation (Lemmon, 2008) and Doppler weather (Greving, 2010) radar systems. As shown in Figure 3, WTI manifests as peaks in range and Doppler frequency in the HF Doppler spectrum that are added to the first order Bragg-scattered signal from ocean waves, or appears in parts of the spectrum that can disrupt the Bragg-scattered signal (Wyatt et al, 2011; Ling 2013; Trockel et al 2018). Both the first order and second order Bragg-scattered signals are used to derive oceanographic data. The Doppler frequencies where the primary peaks

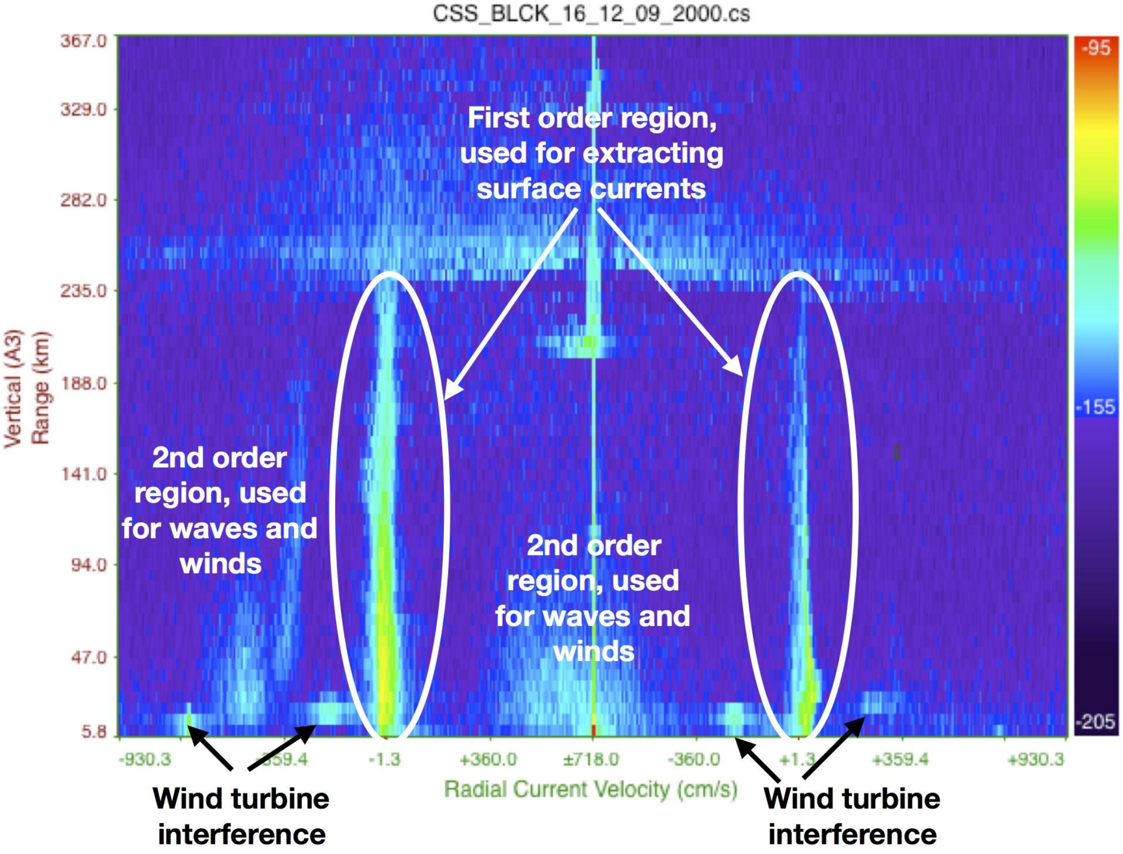


Figure 3: Sample Doppler-Range Spectra, the basic measurement of HF radars that is used to observe the ocean, from a radar system located on Block Island, RI.

and harmonic peaks appear are a function of the turbine blade rate of rotation. The relative amplitude of these peaks are associated with the yaw angle of the turbine relative to the radar. Peaks from multiple turbine echoes in the same range/Doppler bin will add together linearly.

Wyatt et al. (2011) was the first to report on observed impacts of WTI on oceanographic HF radars operating near the Rhys Flats Wind Farm, a relatively small farm in comparison to the footprint of the radar. Subsequent studies (Robinson et al., 2013, 2014) indicated that the radar, a phased array (PA) system using beamforming (BF) techniques, showed elevated errors compared with in situ current measurements when the radar beam pointed to locations away from the wind farm. However, in the area of the wind farm or during lower sea states, there were many data outliers and generally poorer comparisons with in situ instruments. Wave measurements from the 2nd order sea echo, generally of lower signal strength, were impacted more severely than 1st order sea echo from which currents are derived.

Teague et al. (2012) were the first to model the turbines in Numerical Electromagnetic Code (NEC) using a wire model for blades and mast to determine the radar cross section (RCS) at HF for various orientations of three-blade turbines. Periodic RCS variability was identified as the underlying mechanism for the harmonic peaks that appear in HF radar spectra. Naqvi et al. (2013) conducted a simulation-based study that expanded the periodic RCS analysis to scattering from a small wind farm (nine turbines) and focused solely on turbines echoes in the absence of other targets (sea echoes, vessels, etc.). Effects due to either intra-turbine or inter-turbine multiple scattering were shown to exist but were fairly weak and the shadowing effect of a wind farm was found to not be significant on HF radar backscattered signals.

Initial steps toward mitigating WTI were made by the study documented in Trockel et al. (2018). This most recent effort developed equations for calculating the position and relative amplitude of WTI harmonic peaks in HF radar range-Doppler spectra based on generalized turbine and radar parameters. Simulation software was developed for modelling a single turbine operating in a single HF radar range cell, which was validated against real WTI from the five-turbine Block Island Wind Farm impacting 5 and 25 MHz SeaSonde compact cross loop (CCL) systems. This was the first observed WTI in Doppler spectra from SeaSonde CCL systems, which comprise most installed systems world-wide. By adding simulated turbine interference to observed Doppler spectra prior to the presence of the five turbines, studies of the impact of the WTI peaks on uncontaminated spectra were performed. Three primary impacts were identified:

- WTI mixed with Bragg-scattered signals of the ocean currents cause direction finding errors,
- turbine peaks near 1st order Bragg scatter peaks cause erroneous 1st order identification leading to large ocean current errors, and
- turbine peaks raise the background noise floor, reducing the dynamic range of ocean current signals that can be captured by the radar.

Trockel et al. (2018) also explored several potential mitigation strategies using data collected from the Block Island wind farm, including: identifying and removing contaminated ranges (i.e. Figure 4), identifying and removing contaminated range-Doppler results, as well as efforts to correct radial velocities in contaminated areas. Of those tested with the Block Island data, the most effective mitigation method removed contaminated range-Doppler results, which requires solutions to both the forward and inverse problem. The forward problem consists of estimating the magnitude and location of the WTI in the range-Doppler spectra given the turbines' spin rate, yaw angle, and location. The inverse problem seeks to obtain the turbines' spin rate, yaw angle, and location given the magnitude and location of the interference in the observable portion of range-Doppler spectra. The mitigation strategy used the inverse problem to get estimates of the wind turbines operation parameters by using interference outside of the Bragg region, and then used the forward problem to estimate the WTI in the Bragg region and throughout the Doppler

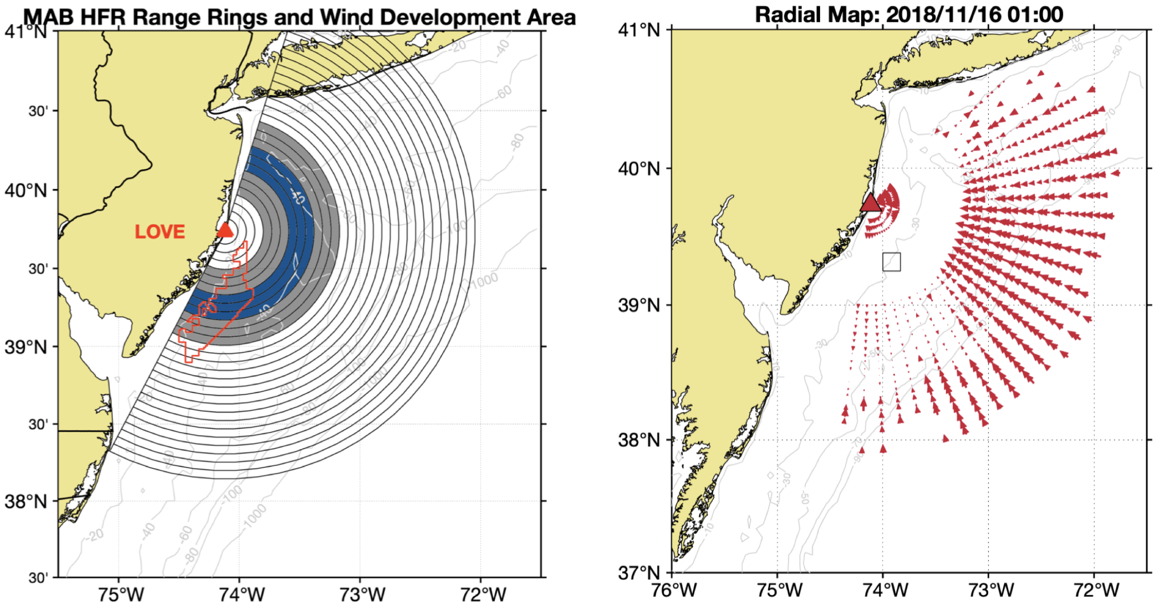


Figure 4: Radar coverage from the Loveladies, NJ, SeaSonde CCL radar system (LOVE) operated by Rutgers University with the range cells of an offshore wind energy development area. Range cells overlapping the wind energy area are marked (left) and eliminated from the observational data product (right), representing the worst case scenario mitigation product.

spectra. Mitigation techniques that removed wind turbine interference from the Bragg region alone were found to be insufficient.

Providing detailed suggestions for next steps, Trockel et al. (2018) was careful to emphasize the need to develop more comprehensive and accurate simulation tools with the capability to simulate WTI from many more turbines. Additionally, their effort was not able to quantitatively assess the magnitude of the error reductions, in terms of velocity errors, due to mitigation methods or the potential for data/coverage losses due to mitigation of the interference.

Thus, additional efforts are required to improve the accuracy of solutions to the inverse problem, and increase the capability to separate WTI and ocean current data (i.e. correcting the radial velocities), rather than simply discarding it as is shown in Figure 4. It should also be noted that, while analysis of the impacts of WTI on HF radar range-Doppler spectra processing since 2015 have been focused primarily on compact, crossloop antenna systems, many of the mitigation strategies identified by Trockel et al. (2018) can in theory be applied to PA radar systems running in either direction finding (DF) mode or beam forming (BF) mode.

## D-Required Mitigation Activities

### *D.1 Approach*

It is likely that numerous offshore wind energy installations will exist in the U.S.'s outer continental shelf within the next 10 years and thus, *HF radar systems need to adapt to provide observations in areas both exposed to WTI as well as within the areas of wind farms themselves*. This is critical for NOAA-IOOS as a data aggregator of environmental data over the outer continental shelf (OCS) as well as for our collective —government, research, and industry—need for environmental intelligence within the OCS.

A greatly increased pace of mitigation research is needed. This research must be collaborative among the federal agencies (e.g. NOAA, DOE-EERE, DOI-BOEM) who have expertise and oversight authority on energy, oceanic, or environmental permitting issues, as well as collaboration among the companies that manufacture and sell HF radars for ocean sensing and the university-researchers who own and operate the majority of U.S.-based operational systems. Anything less than a fully coordinated process will delay the development and testing of effective mitigation strategies and lead to the loss of situational awareness and critical long-term monitoring results.

As the initial efforts of Trockel et al. (2018) focused on the effects of an individual turbine, additional efforts to understand WTI from arbitrary numbers of wind turbines is a required step towards determining the true impact of larger wind farms. Furthermore, it is essential to find and assess potential mitigation measures for both removal and/or correction of impacted data that have applicability across the full range of HF radar systems and potential radar-turbine interferences. While this document focuses mostly on HF radar-based estimates of surface currents and their mitigation due to WTI, it is critical to note that other important data products rely on information contained in the 2nd order portions of the Doppler spectrum (see Figure 3). These portions will also be heavily affected by WTI and will limit future use of HF radar observations of wave conditions, ship tracking, and automatic calibration measurements. Work to mitigate these impacts will require an additional process that is beyond the scope of the present document.

### *D.2 Required Activities*

#### *D.2.1 Determine recommended HF radar operational parameters*

The adjustment of at least two parameters, the sweep rate and fast-Fourier transform (FFT) length, may simplify efforts to mitigate wind turbine interference in HF radar data (Ling et al. 2013; Trockel et al. 2018). Oceanographic HF radar systems sweep at slow rates, typically 1-4 Hz, since the target velocities (surface gravity waves and vessels) tend to be slow moving. Because the sweep rate of the radar signal determines the resolvable range of Doppler frequencies, relatively slow sweep rates cause higher frequency signals (like wind turbine blade echoes) to become aliased into the Doppler spectra. This means that the WTI appears in range cells and Doppler-frequency bins other than those of the actual source of the interference.

The effects of WTI aliasing on HF radar observations collected with different sweep rates can be illustrated with two examples, as shown in Figure 5. In the top panel, the sweep rate is set to 1 Hz, which limits the Doppler window to ±0.5 Hz. The diagonal lines indicate the Doppler frequencies where discrete wind turbine peaks for the first four positive and negative harmonics occur for a typical range of turbine rotation rates (0-12 rpm; vertical axis). As the rotation rate increases, the interference peaks spread out and approach the edge of the Doppler window. When they spread beyond the edge of the Doppler window, they reenter from the opposite edge and are aliased to new Doppler frequencies, potentially multiple times. Thus, in this first example, aliasing significantly complicates the relationship between the turbine operational parameters (including rotation rate) and the location of signal in the range-Doppler space (i.e. Figure 4). In the bottom panel of Figure 5, the sweep rate is set to 5 Hz with Doppler window edges of ±2.5 Hz. With the wider Doppler window shown, aliasing does not occur for rotation rates below 12 rpm. Thus, the potential for aliasing complication increases the probability of impacts to ocean

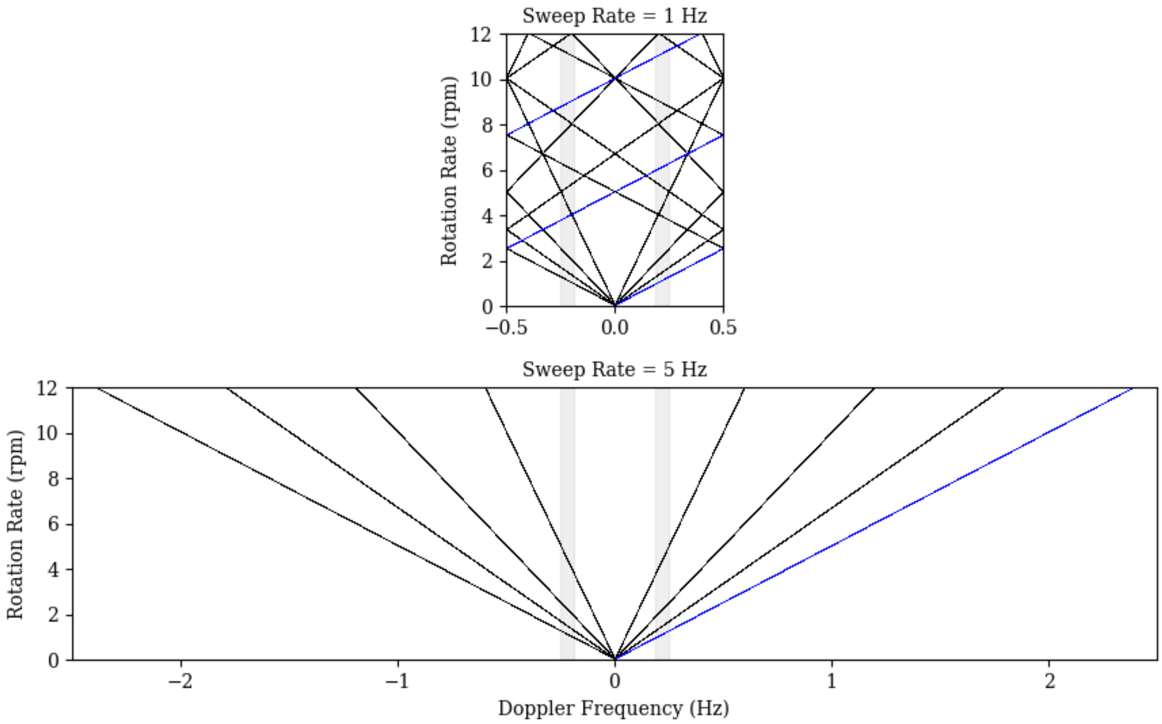


Figure 5: Illustrating the effect of sweep rate on HF radar aliasing of WTI: the Doppler frequencies of the primary WTI and first three harmonics for a range of rotation rates for a radar transmitting with a 5 MHz center frequency and sweep rates of (top) 1 Hz, and (bottom) 5 Hz. In both panels, the region where surface currents would likely be detected is shaded grey. Each line represents the location of a WTI peak in the Doppler window for a given rotation rate. The blue line tracks the location of one such WTI signal through both panels.

current observations. In Figure 5 when the sweep rate is high enough to prevent aliasing, the WTI does not show up in the Bragg regions after 5 rpm. However, when the sweep rate does not prevent aliasing the WTI  continues to enter the Bragg regions after 5 rpm. The problem becomes further complicated when considering the possibility of multiple turbines located in a radar's coverage area, operating at different rotational rates.

The sweep rate works in conjunction with other settings to affect how HF radar data is collected. For example, experiments altering the sweep rate will have to consider adjustments to the length of the FFT used to derive the Doppler spectrum in order to maintain an adequate integration time.  However, the optimal Doppler spectrum integration time should also be investigated as it impacts the width and signal-to-noise ratio (SNR) of the wind turbine interference peaks. Changes to the operational parameters of a radar to minimize the potential for interference should be evaluated first via simulation experiments of the radar and wind farm in question. Once a recommended sweep rate has been determined, field testing will be required to confirm that aliasing has been eliminated and that no other adverse consequences of the increased sweep rate exist.  A necessary outcome of this activity is to provide HF radar operators with well documented recommendations for radar settings (sweep rate, FFT integration time, etc.) when operating in view of wind turbines and wind farms.

### *D.2.2 Further develop wind turbine interference modelling capabilities*

Simulations enable cost effective means to improve our understanding of the effects of interference, test mitigation methods, and estimate the potential impact of wind farms on HF radar data. To enable these capabilities, it is necessary to improve and expand upon the interference modelling techniques developed by Trockel et al. (2018). This model was used to study mitigation methods for interference resulting from 1-5 wind turbines, all of similar type. Further research is needed to generalize the model's ability to simulate the large numbers of proposed turbines.

Steps to expand the simulation tools developed by Trockel et al. (2018), include adding capabilities to model:

- Interference from an arbitrary number of wind turbines, over a wide spatial area, and variable angles relative to the radar.
- Variable turbine rotation rates - both among turbines, and for a single turbine on timescales less than the Doppler FFT integration time.
- Variation in the radar sweep rate.
- Variation in the material properties of the wind turbine (and signal scattering properties, e.g RCS).
- Interfering signal scaling factors, including attenuation due to surface wave losses over range.
- Received signals for general oceanographic radar receive arrays.

- Impacts to HF radar observational errors and data coverage.

A calibrated simulator will have the ability to output spectra for both CCL and PA radar systems, which will allow theoretical predictions of WTI impacts on these systems. The small impact seen previously on PA systems (Wyatt et al., 2011) can be reassessed for new wind farm installations by modelling the antenna pattern of the PA radar antenna array (usually 8-16 element linear arrays) and using the calibrated simulator output. A necessary outcome of this activity is a community software toolbox for simulating WTI with range-Doppler spectra.

### *D.2.3 Develop research data sets*

In order to consistently compare the efficacy of proposed mitigation techniques, it is necessary to form a robust validation data set. We propose a three-tiered validation data set, consisting of (1) simulated data, (2) a hybrid data product of field HF radar range-Doppler spectra with simulated WTI, and (3) field data of HF data with real WTI. A simulated data set consisting of spectra completely made using the model developed above, and including simulated currents and other forms of interference would be useful for testing the mitigation of specific impacts in a controlled environment. However, since a simulation can never capture all the variability found in field data, a hybrid data set should be constructed by adding simulated wind turbine interference to range-Doppler spectra collected in the field. The hybrid data set has the benefit of having realistic background variability while still allowing the independent adjustment of turbine rotation rates and yaw angles. Using existing HF radar data sets in a variety of locations, WTI from simulations of planned wind farms can be added to spectra of known quality. This would allow impacts of a variety of wind farm designs to be assessed. Lastly, a field data set consisting of HF radar spectra with WTI, along with the turbine rotation rates and yaw angles, should be obtained. Ideally, the wind turbine operational data would be provided through a partnership with turbine operators. However, if unavailable, the wind turbines' status could be obtained from video recordings in some limited cases as in Trockel et al., 2018.

Observational data should include range dependence and amplitude scaling of wind turbine interference, at a minimum. It is critical to construct a data set spanning a variety of turbine configurations and types, as well as a variety of HF radar types. Doppler spectra from low, mid, and high (e.g. 5, 13 and 25 MHz) frequency HF radars at several ranges from an operational wind farm should be collected, ideally during a wide range of wind conditions (i.e. turbine rotation rates and yaw angles).

### *D.2.4. Develop non-excising mitigation strategies*

Methods for separating data affected by WTI, rather than removing them (e.g. Figure 4), need to be developed and tested. Trockel et al. (2018) showed that if the rotation rate of a turbine is known, it is possible to know which areas of the range-Doppler spectra will be impacted (e.g. Figure 5). This led to the proposed mitigation strategy of using an inverse method to infer the rotation rates and yaw angles of the turbines from WTI in the 2nd order areas of the range-Doppler spectra, and then using these to model the WTI throughout the entire spectrum. Range-Doppler regions containing interference can then be flagged for removal, or separated through some mathematical method.

These types of data-based methods to infer the wind turbine parameters (i.e. *the inverse problem*) could be improved by incorporating the temporal history, the spatial structure of the interference in range-Doppler space, the rotation rate estimations from secondary radars, or the antenna power ratios. *In particular, improved estimates of the relative amplitudes of the turbine peaks are critically needed, both for the individual turbines, and the large number of turbines in planned wind farms.* With each improvement to the inverse model, the statistical significance of the turbine state estimation should increase, which will improve the accuracy of WTI estimates and increase the opportunities to separate ocean current data and WTI, rather than simply throwing it away.

A complementary effort is required to assess the impact of WTI on Bragg-region determination, the identification of the boundary between the 1st order and 2nd order regions of the range-Doppler spectra. The observation-based research data sets should be examined to determine how often WTI is within the Bragg region, or alters the definition of the Bragg region. This effort should focus on developing methods that will:

- reduce the effects of WTI on the range-Doppler noise floor estimates,
- correctly identify erroneous ocean current velocities, and
- utilize non-velocity metrics to conduct quality control on data from both DF and BF systems.

### *D.2.5 Validation field studies*

Intensive field efforts will be required to confirm WTI mitigation success at the first major wind farm installations. Once the research data set described in D.2.3 has been created, and preliminary mitigation methods are available (outcome of D.2.4), i.e. achieving technical readiness levels (TRL) of 5 to 6, a carefully designed validation and WTI impact study should be undertaken. To fully validate the mitigation approaches, this effort must pair multi-frequency radar observations of the areas in and surrounding the wind farm with multiple, in situ observations of the near-surface currents, winds and wave climates, including but not limited to drifter releases. The effort should be able to document the effectiveness of mitigation approaches and be evaluated based on a series of analysis tests, including the:

- Error in the resulting surface current measurements and its spatial dependence,
- Dependence of mitigation need and method success based on oceanic conditions (e.g. wave climates),
- Loss of good data and amount of corrupted data that remains,
- Impact to the first order line settings,

- Impact on secondary data products (i.e., waves, winds, vessels detection, tsunamis, automatic antenna pattern generation),
- Computation expense and scalability of the method.

### *D.3-Additional Activities*

#### *D.3.1 Mitigating via advanced direction finding methods*

Trockel et al. (2018) found that the Doppler velocity signal from wind turbines can overlap with signals from ocean currents, creating a situation where signals with the same radial velocity arrive from more than two directions simultaneously. Direction finding methods used by oceanographic HF radars can separate up to M-1 signals coming from different directions, where M is the number of antennas. The standard SeaSonde CCL has M=3 which might impose limitations on the resolvable ocean current field when operating with one or more wind turbines in a range cell. It may be possible for an HF radar with sufficient M to separate the wind turbine signals from the ocean current signals at the direction finding step, and recover the ocean currents separately and intact. We suggest investigating this capability with both simulated and deployed systems with M>3. Recent research (Emery et al., 2019) suggests that even in a situation where the radar is able to resolve the different signals (WTI and currents), there will be an impact on the accuracy of the ocean current observations. Thus questions to be resolved include: (1) what is the sufficient or recommended M when observing currents in and around wind farms? (2) What is the impact to the ocean current observations in terms of RMS error? (3) Is separation at the DF step sufficient, or is further signal processing required (such as Kalman Filtering or other detection and separation of the WTI signals)?

#### *D.3.2 Additional assessment field studies*

Efforts to understand the impact on the other HF radar data products should also be undertaken. While this report focuses on the mitigation of surface currents only, given the resources needed to collect the research data sets (D.2.2) as well as the validation field studies (D.2.5) it would be most cost-effective for future studies to ensure that critical validation parameters for wave and wind extractions, ship tracking, etc. were also collected at these initial efforts.

Additionally, inherent differences in the wave climates between the East and West Coasts of the U.S. (i.e. more narrow-banded swell on the West Coast) might lead to variations in the efficacy of the mitigation strategies developed during the initial efforts that are more likely to be focused on the U.S. East Coast. It is suggested that a second validation effort be conducted in an area with both potential wind farms and different operational parameters to further test and validate WTI mitigation methods.

#### *D.3.3 Implementation of real time, autonomous WTI mitigation*

The initial efforts, described above, will be able to bring mitigation techniques through the advanced testing and validation steps. Additional, follow on efforts will be required to implement these mitigation techniques as operational software packages that are available to radar operators (commercially and/or otherwise). In terms of a TRL, these final efforts would move the mitigation methods from a TRL of 6 to 7 to the maximum level of 9, rendering them available to any and all HF radar operators that require their use for autonomous mitigation.

## E-Suggested Timeline for Mitigation Research Activities

### *E.1-Near-Term (0-6 months):*

1. Continue data collection at HF radar systems in view of the Block Island Wind Farm; including mid-range (i.e. 13-16 MHz) systems and different radar site locations.

2. Investigate and test changes to HF radar operational parameters (i.e. sweep rate modifications) and produce a 'best practices' document summarizing present ways to mitigate WTI effects.

3. Further develop wind turbine interference modelling capabilities to enable fully arbitrary radar and wind farm configurations.

### *E.2-Mid-Term (6 months to 2 years):*

1. Conduct model calibration studies based on data from initial field studies and work to improve solutions to the inverse problem.

2. Develop a focused research dataset (with simulated data, hybrid datasets, and observed WTI) that spans the parameter space needed to provide sufficient observations/tests for initial validation efforts. Conduct any simulations or preprocessing needed to create, document, and distribute the research dataset as a publicly available archive.

3. Investigate integration time modifications (range-Doppler spectral time interval) and other follow-ons to sweep rate modifications that have the potential to reduce mitigation needs and/or increase the accuracy of the mitigation methods.

4. Conduct field studies for the validation dataset with high quality radar coverage and in situ sensor deployments at the first major wind farm in U.S.. These datasets will be used to confirm WTI effects, calibrate simulation models, and track mitigation effectiveness.

5. Build and test initial mitigation solutions using the research dataset and simulation tools, moving concept testing from TRLs of 4 or 5 to 7.

### *E.3-Long Term (2-5 years):*

1. Use the validation datasets to test and document the efficacy of proposed mitigation approaches for typical radar configurations.

2. Conduct secondary field validation effort at alternative locations that encompass different parameter regimes for turbine, radar, and ocean conditions.

3. Move mitigation solutions to a TRL of 9.

4. Conduct mitigation development and testing for 2nd order and advanced data products available from oceanographic HF radars. Use existing research dataset and validation dataset for these efforts.

**F- References**

Emery, B. M., 2019: Evaluation of Alternative Direction of Arrival Methods for Oceanographic HF Radars. *IEEE Journal of Oceanic Engineering*.

Greving, G. and M. Malkomes, 2010: Weather radar and wind turbines-an update of the theoretical and numerical analysis of effects. In *Proceedings of the 6th European Conference in Meteorology and Hydrology*, pp. 1–5.

Harlan, J., A. Allen, E. Howlett, E. Terrill, S. Y. Kim, M. Otero, S. Glenn, H. Roarty, J. Kohut, J. O'Donnell, et al., 2011: National IOOS high frequency radar search and rescue project. In *OCEANS'11 MTS/IEEE KONA*, IEEE, pp. 1–9.

Harlan, J., E. Terrill, L. Hazard, C. Keen, D. Barrick, C. Whelan, S. Howden, and J. Kohut, 2010: The integrated ocean observing system high-frequency radar network: status and local, regional, and national applications. *Marine Technology Society Journal*, 44(6), 122–132.

Lemmon, J. J., J. E. Carroll, F. H. Sanders, and D. Turner, 2008: Assessment of the effects of wind turbines on air traffic control radars. *National Telecommunications and Information Administration Technical Report*, (08-454).

Ling, H., M. F. Hamilton, R. Bhalla, W. E. Brown, T. A. Hay, N. J. Whitelonis, S. T. Yang, and A. R. Naqvi, 2013: Final report DE-EE0005380: Assessment of offshore wind farm effects on sea surface, subsurface and airborne electronic systems. Tech. rep., University of Texas, Austin, TX; Science Applications International .

Naqvi, A. and H. Ling, 2013: A study of radar features of wind turbines in the HF band. *Progress In Electromagnetics Research*, 143, 605–621.

Robinson, A., 2013: *Wind turbine impacts on HF radar ocean surface measurements in Liverpool Bay*. Ph.D. thesis, University of Sheffield.

Sengupta, D. L. and T. B. Senior, 1979: Electromagnetic interference to television reception caused by horizontal axis windmills. *Proceedings of the IEEE*, 67(8), 1133–1142.

Shay, L. K., H. E. Seim, D. Savidge, R. Styles, and R. H. Weisberg, 2008: High frequency radar observing systems in SEACOOS: 2002-2007 lessons learned. *Marine Technology Society Journal*, 42(3), 55–67.

Teague, C. C. and D. E. Barrick, 2012: Estimation of wind turbine radar signature at 13.5 mhz. In *2012 Oceans*, IEEE, pp. 1–4.

Trockel, D., I. Rodriguez-Alegre, D. Barrick, C. Whelan, J. Vesesky, and H. Roarty, 2018: Mitiga- tion of offshore wind turbines on high-frequency coastal oceanographic radar. In *OCEANS 2018 MTS/IEEE Charleston*, IEEE, pp. 1–7.

Wyatt, L., A. Robinson, and M. Howarth, 2011: Wind farm impacts on hf radar current and wave measurements in liverpool bay. In *OCEANS 2011 IEEE-Spain*, IEEE, pp. 1–3.

## Appendix A - Working Group Membership

Anthony Kirincich (lead)
Associate Scientist
Woods Hole Oceanographic Institution
akirincich@whoi.edu

Douglas Cahl
PhD Student
University of South Carolina
dcahl@geol.sc.edu

Brian Emery
Assistant Researcher
University of California, Santa Barbara
brian.emery@ucsb.edu

Mike Kosro
Professor
Oregon State University
kosro@coas.oregonstate.edu

Hugh Roarty
Research Project Manager
Rutgers University
hroarty@marine.rutgers.edu

Dale Trockel
Data Scientist
CODAR Ocean Sensors
dale@codar.com

Libe Washburn
Professor
University of California, Santa Barbara
libe.washburn@ucsb.edu

Chad Whelan
Chief Technology Officer
CODAR Ocean Sensors
chad@codar.com

# Appendix B - Working Group Charge

Begin forwarded message:

**From:** Derrick Snowden - NOAA Federal <derrick.snowden@noaa.gov>
**Subject: Wind Turbine Interference Plan**
**Date:** April 9, 2019 at 11:59:41 AM EDT
**To:** Anthony Kirincich <akirincich@whoi.edu>

Dear Anthony,

Thanks for your letter and for the conversations this past week. I appreciate your perspective and your desire to push for change. With Jack gone, I'll temporarily step in to the interagency Wind Turbine Radar Interference Mitigation Working Group. In order to best represent NOAA, IOOS and the HF Radar community I am going to need to rely on the technical expertise of our HFR science and operator community. In addition to serving on the working group, I will be trying to cover the essential duties the previous PM performed while working to hire a new Program Manager for the IOOS Surface Current Program which can be a lengthy process in the federal government. Wind turbine interference is an important threat to the HF network operations and deserves attention in the near future but also will require a longer term plan. I would very much appreciate your assistance in organizing the community to come up with near (~1 month), mid (~6 months) and longer term (> 1year) recommendations for understanding the threat wind turbines present and mitigating this threat in a way that addresses the entirety of the HF network operations (i.e. observing platform agnostic, to the extent scientifically feasible).

One important element of these recommendations should be a description of the previous BOEM funded assessment study along with a summary of what remains to be understood and how those advances might be implemented. Even understanding the origins of the study in the BOEM organization would be helpful. Why are they interested in funding this work and what might make proposals for follow on work likely to succeed?

I welcome a conversation at any time on this and I appreciate your proactivity so far.

Best regards,
Derrick

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Derrick Snowden
Chief, Operations Division
U.S. Integrated Ocean Observing System Program
+1 240 533 9467 (o); +1 240 778 9129 (c)
Facebook | Twitter

## Appendix C - Abbreviations Used

| | |
|---|---|
| BF | Beam Forming |
| BOEM | Bureau of Ocean Energy Management |
| CCL | Compact Cross Loop (SeaSonde receive antenna) |
| DOE | U.S. Department of Energy |
| DOI | U.S. Department of the Interior |
| EERE | Office of Energy Efficiency and Renewable Energy |
| FFT | Fast Fourier Transform |
| HF | High Frequency |
| IOOS | U.S. Integrated Ocean Observing Systems |
| MW | Megawatt |
| NEC | Numerical Electromagnetics Code |
| NM | Nautical Mile |
| NOAA | National Oceanic and Atmospheric Administration |
| OCS | Outer Continental Shelf |
| PA | Phased Array (receive antenna) |
| RCS | Radar Cross Section |
| RMS | Root Mean Square |
| WTI | Wind Turbine Interference |