U.S. DEPARTMENT OF ENERGY

Update on the Efforts of the Wind Turbine Radar Interference Mitigation Working Group

Report to Congress
February 2024

United States Department of Energy
Washington, DC 20585

Message From the Secretary

Pursuant to statutory requirements, this report is being provided to the following Members of Congress:

- **The Honorable Patty Murray**
  Chair, Senate Committee on Appropriations

- **The Honorable Susan Collins**
  Vice Chair, Senate Committee on Appropriations

- **The Honorable Patty Murray**
  Interim Chair, Energy and Water Development Subcommittee
  Senate Committee on Appropriations

- **The Honorable John Kennedy**
  Ranking Member, Energy and Water Development Subcommittee
  Senate Committee on Appropriations

- **The Honorable Kay Granger**
  Chairwoman, House Committee on Appropriations

- **The Honorable Rosa DeLauro**
  Ranking Member, House Committee on Appropriations

- **The Honorable Chuck Fleischmann**
  Chairman, Energy and Water Development Subcommittee
  House Committee on Appropriations

- **The Honorable Marcy Kaptur**
  Ranking Member, Energy and Water Development Subcommittee
  House Committee on Appropriations.

If you have any questions or need additional information, please contact me or Meg Roessing, Deputy Director for External Coordination, Office of Budget, Office of the Chief Financial Officer, at (202) 586-3128.

Sincerely,

Jennifer M. Granholm

Executive Summary

This report responds to language set forth in the House Committee on Appropriations Report 117-98, which accompanied the Energy and Water Development and Related Agencies Appropriations Bill (2022).

As wind turbines continue to expand in both size and number, they can interfere with radar systems. The clutter created by wind turbines typically increases the false alarm detection rate of a radar. To suppress this, the radar system will raise the threshold for what is considered a detection and, as a result, may miss actual targets.

While there are many types of radar systems, the systems that this report focuses on are broadly categorized into four types: terminal, long-range, high-frequency, and weather. These systems support air traffic control and flight safety, severe weather forecasting and warnings, coastal sea-surface and maritime surveillance, oceanographic measurements, and homeland and national defense missions. To date, no mitigation technology has been able to fully restore the technical performance of impacted radars. However, the development and use of radar interference mitigation techniques, and collaboration both among federal agencies and between the federal government and the wind industry have enabled federal radar agencies to continue to perform their missions without significant impacts, and have also enabled significant wind energy deployments throughout the United States which produced more than 9% of the United States' electricity in 2021 [1].

The Report describes the efforts of the Federal interagency Wind Turbine Radar Interference Mitigation (WTRIM) working group, which was established by a consortium of Federal agencies including the U.S. Department of Defense (DOD), U.S. Department of Energy (DOE), Federal Aviation Administration (FAA), and National Oceanic and Atmospheric Administration (NOAA) to address the impacts of wind turbines on civilian and national defense radar system operations.[1] Each agency that voluntarily participates in the WTRIM working group receives its own annual appropriations and direction from Congress.[2]

The Report also provides a broad overview of options to mitigate wind turbine radar interference, as well as the status of some specific mitigation strategies and technologies that have been studied. These include wind farm siting and operations, reduced signal wind turbines (turbine design changes to reduce amount of energy reflected to the radar system), radar

[1] The U.S. Department of Homeland Security (DHS) and Bureau of Ocean Energy Management (BOEM) have been observers of the WTRIM working group, with BOEM becoming a full participating member in 2018.

[2] Portions of these agencies' funds have been used to support agency-focused research, development, and demonstration of wind turbine radar interference mitigation activities. DOE's Wind Energy Technologies Office requested input from the federal WTRIM working group on the status of past, current, and planned activities to reduce wind turbine impacts on civilian and defense radar systems.

upgrades, command and control automation upgrades, augmentation radars, and replacement radars.

The report concludes with detailed information on the mitigations options currently being developed and tested, mitigation solutions that are not being considered because of resource constraints, and mitigation options that have been dismissed and explains why they are not considered viable.

Key findings from the report are summarized below:

- Wind turbines that are located within the line-of-sight[1] of civilian and defense radar systems are known to cause interference which impacts radar performance, and in turn can negatively impact the missions that depend on those radars.
- Testing campaigns to date have been successful in characterizing interference issues with each radar type tested and increasing the technical understanding of the interference issues.
- Wind farm siting tools have been developed and are available to assist in analyzing potential wind turbine impacts on federal radar systems.
- The most basic and widely-employed mitigation method is wind farm siting, such as modifying the layout a proposed wind farm to keep the wind turbines out of the line-of-sight of the radar.
- Wind farm operational agreements have also been employed as a means of mitigating impacts to radar systems, including curtailment agreements to reduce the speed of the wind turbine blades for special events. In less straightforward cases, a mitigation agreement may be negotiated that requires either changes to the operation of the wind facility or that industry funds a mitigation upgrade to the existing radar system.
- Reducing the radar cross section of a wind turbine blade by integrating radar-absorbing material could achieve a limited reduction in interference though not enough to satisfy the cost to manufacturers and the limited ability to enhance radar performance.
- Radar software upgrades for long-range radars have had moderate success at improving the ability of the radars to operate in areas with high wind turbine deployment. However, with the anticipated development of additional wind farms, these software upgrades may not be enough to mitigate the impacts.
- Replacement radar and infill radar solutions are the most viable technology mitigation solutions to enhance degraded radar performance in areas above wind turbines.

Going forward, wind energy will play a leading role in the nation’s transition to a clean energy economy. Continued progress in radar interference mitigation will be important for ensuring

[1] Radar line-of-sight refers to the region above the Earth’s surface which the energy transmitted by the radar can reach. There are limits to the reach of radar signals which can be caused by the transmitter power of the radar, the curvature of the Earth, and/or terrain obstructions.

access to high wind resource areas by developers. Interagency collaboration and coordination must continue in order to define solutions that will allow large-scale wind deployment.

Update on the Efforts of the Wind Turbine Radar Interference Mitigation Working Group

Table of Contents

I. Congressional Language

This report responds to language set forth in the House Committee on Appropriations Report 117-98, which accompanied the Energy and Water Development and Related Agencies Appropriations Bill (2022). On page 115, Report 117-98 states:

> *"The Committee is aware of and supports the ongoing work of the Wind Turbine Radar Interference Mitigation working group managed by the Wind Energy Technologies Office. The Department is directed to provide to Committee not later than 180 days after enactment of this Act a report on the efforts of the working group. The report should include the:*
> - *status of testing, certification and deployment of mitigation options by radar type and department or agency;*
> - *remaining steps and timelines before mitigation options currently being developed or tested could be available for deployment;*
> - *identification of resource gaps to achieve deployment of mitigation options currently being tested;*
> - *identification of mitigation options that are not currently being considered due to resource constraints but may be promising with additional resources and prioritization; and*
> - *mitigation options that have been dismissed along with an explanation of why the option is not considered viable."*

II. Wind Energy and Radar Introduction

U.S. wind energy is a competitive and robust source of electricity across the Nation, with more than 136 gigawatts of capacity[3] installed that contributed over 9 percent of total generation in 2021 [1]. This growth of wind energy installations is poised to accelerate due to continued expansion of new economic and environmental benefits, such as lower costs for electricity generation, tens of thousands of well-paying jobs, increased U.S. manufacturing and supply chain opportunities, and significant public-health benefits resulting from improved air and water quality.

Land-based wind energy is a proven, low-cost electricity generation source when deployed at high-quality wind resource locations. Adding to that is an emerging market for offshore wind energy, which will be available in both shallow and eventually deeper waters [2]. Wind energy can also help make the electric grid more reliable and resilient, as well as generate clean fuels to help transition the U.S. economy to zero emissions in the transportation, buildings, industrial, and agricultural sectors.

[3] Capacity is defined as the amount of electricity a generator can produce at its maximum output level.

Radar systems are vital tools used across many missions within the Federal Government, such as homeland defense, flight safety, search and rescue, and weather observation and warning systems.

As wind turbines continue to expand in both size and number, they can interfere with radar systems. This represents a significant challenge as over 40 percent of land-based and over 25 percent of offshore wind resource technical potential is in the field of view of critical radar systems (see Figure 1). The radar systems that are impacted support air traffic control and flight safety, severe weather forecasting and warnings, coastal sea-surface and maritime surveillance, oceanographic measurements, and homeland and national defense missions, all of which can directly affect people's daily lives and property.

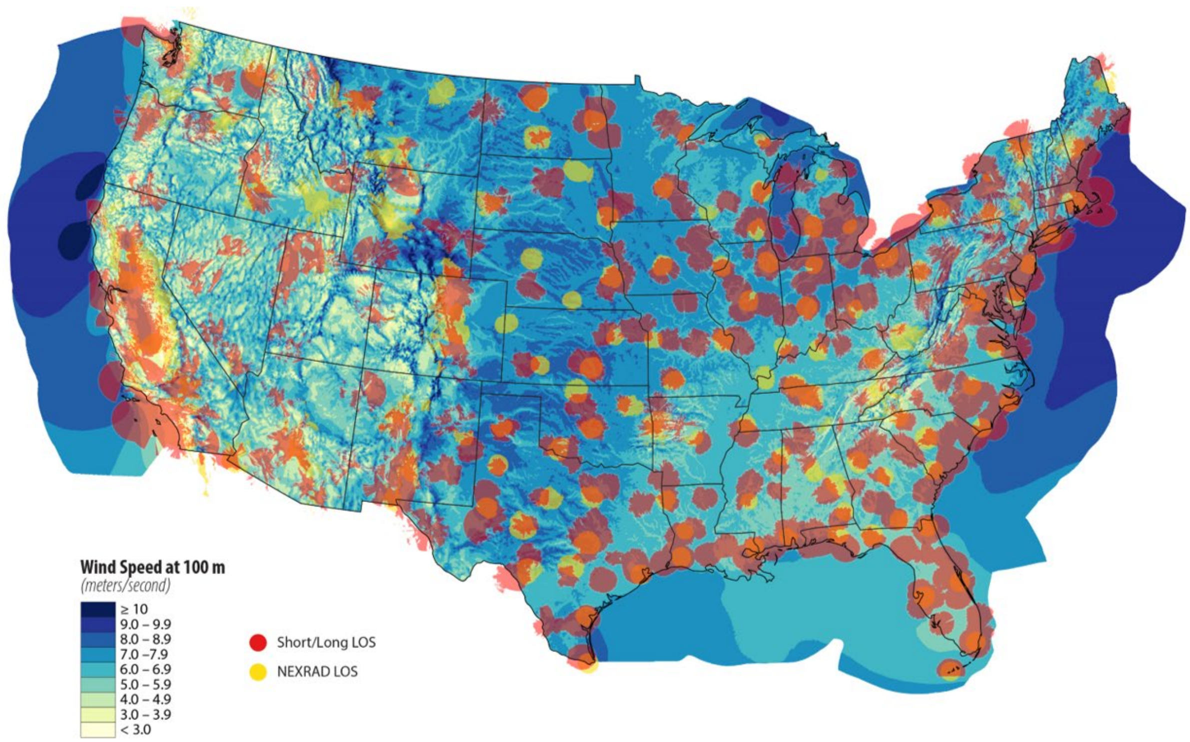
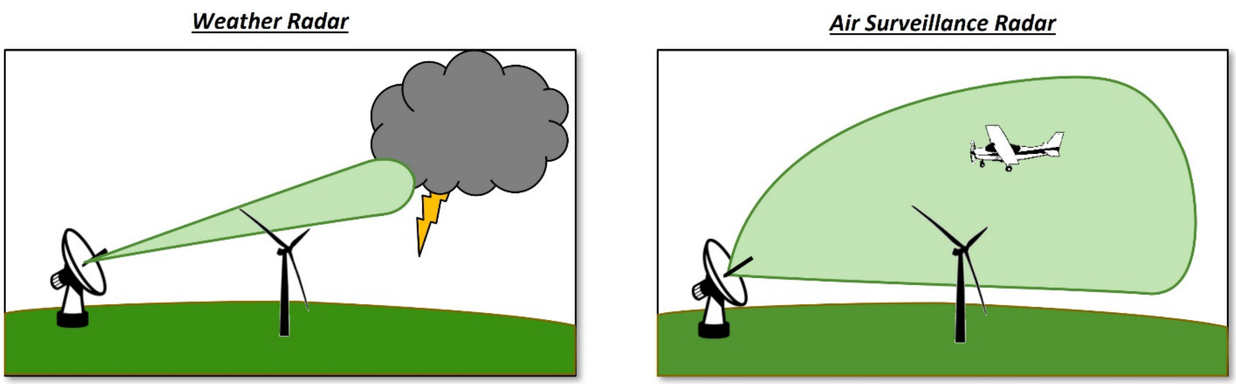


Figure 1 – This map shows radar line-of-sight (LOS) polygons approximated at 100 meters above ground using a simple viewshed analysis based on publicly available radar station locations. The polygons do not represent the actual line-of-sight that can be observed by the scan of a radar system but give an approximation of the potential areas of CONUS where wind turbine build out may impact a radar system. Short/Long (red shading) range refers to air traffic control and air route surveillance radars respectively and NEXRAD (yellow shading) represents weather radars. The yellow and red shading is for visualization purposes only and these areas do not represent no-go zones for wind development. *Image created by the National Renewable Energy Laboratory.*

Wind turbines that are located within the line-of-sight[4] of civilian and defense radar systems are known to cause interference, potentially impacting their ability to perform their mission. For example, interference with weather radar may impede critical weather forecasts. In general, wind turbines can impact radar performance by:

- Creating clutter[5]
- Reducing detection sensitivity
- Obscuring potential targets
- Scattering target returns, which can inhibit target detection
- Hindering target tracking
- Generating false targets



Technical impacts:

- Turbines present unique mix of moving and static clutter
- Decrease probability of target detection
- Increase false alarms
- Corrupt track quality

Mission impacts:

- Flight safety (FAA, DOD)
- Border protection, navigation, search and rescue (DHS)
- Homeland defense (DOD)
- Weather observation and warning, ocean observation (NOAA)

Figure 2 - Wind-radar interference basics. [3]

To date, no mitigation technology has been able to fully restore the technical performance of impacted radars. However, the development and use of radar interference mitigation techniques, and collaboration both among federal agencies and between the federal government and the wind industry have enabled federal radar agencies to continue to perform

[4] Radar line-of-sight refers to the region above the Earth's surface which the energy transmitted by the radar can reach. There are limits to the reach of radar signals which can be caused by the transmitter power of the radar, the curvature of the Earth, and/or terrain obstructions.

[5] Clutter refers to any unwanted return signals to the radar. This can come in the form of man-made structures (i.e., buildings, antennas, etc.), birds, trees, and so on.

their missions without significant impacts and have also enabled significant wind energy deployments throughout the United States.

The clutter created by wind turbines typically increases the false alarm detection rate of a radar. To suppress this, the system will raise the threshold for what is considered a detection and, as a result, the radar may miss actual targets. For national weather radars (Next Generation Weather Radar [NEXRAD] systems) and coastal high-frequency radars, existing technologies can only reduce, but not eliminate, the interference caused by wind turbines of true weather signals. Coastal high-frequency and over-the-horizon radar systems add to the complexity because they are impacted by multiple electromagnetic pathways. With these systems, the radar signals are affected by objects above the ground and at the ground or sea surface.

While there are many types of radar systems, the systems that this report is interested in can be broadly categorized into four types: terminal, long-range, high-frequency, and weather.

Terminal radar systems include surveillance radars known as Airport Surveillance Radars (ASR). These radar systems provide short-range (60 nautical miles) coverage near airports and serve as a tool to manage terminal air traffic [4]. They include the ASR-8, ASR-9, ASR-11, and DASR.

Long-range radar systems, used by the FAA, DOD, and DHS, include surveillance radars known as Air Route Surveillance Radars (ARSR). As the name implies, these radar systems provide long-range (200–250 nautical miles) coverage to detect and track targets over large areas. Targets can include anything in the airspace from commercial aircraft to non-cooperative homeland threats [4]. They include the ARSR-4, and the Common Air Route Surveillance Radar (CARSR).

High-frequency radar systems used by NOAA and the U.S. Coast Guard measure the speed and direction of ocean surface currents. These radar systems have coverage areas up to 100 nautical miles from the shore and are used to aid in marine navigation, hazardous materials spills, search and rescue, and water quality monitoring [5].

Another type of high-frequency radar system is called the Relocatable Over-the-Horizon Radar (ROTHR) used by the Department of Defense. This is a long-range system that utilizes the ionosphere to detect targets up to 1,600 nautical miles away and is primarily used for drug interdiction [6].

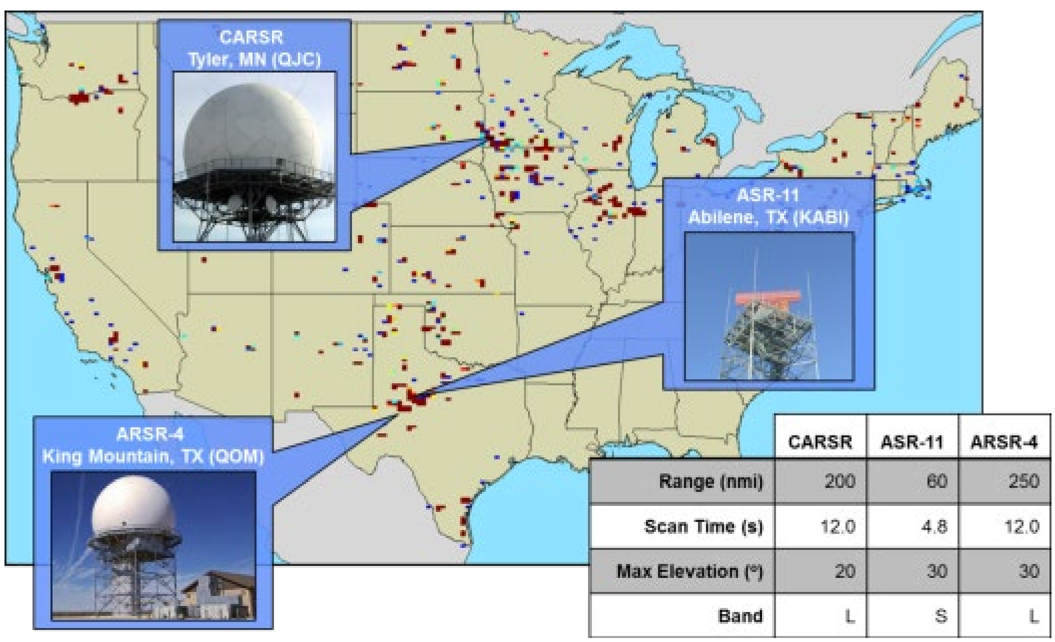
Weather radar systems provide near real-time information on storm systems and are used to issue severe weather warnings. These systems include the Weather Surveillance Radar, 1988 Doppler (WSR-88D), also known as NEXRAD. There are 160 NEXRADs in operation in the United States and they can have a coverage of up to 250 nautical miles [7].

III. Wind Turbine Radar Interference Mitigation Working Group Overview

Active research in the radar interference space began in 2012 with the Interagency Field Test & Evaluation (IFT&E) campaign, funded by DOE, DOD, DHS, and the FAA, to:

- Characterize the impact of wind turbines on existing program-of-record air surveillance radars.
- Assess near-term technologies proposed by industry that have the potential to mitigate the interference from wind turbines on radar systems; and
- Collect data and increase technical understanding of interference issues to advance development of long-term mitigation strategies [8].

Under this campaign, the Massachusetts Institute of Technology's Lincoln Laboratory (MIT LL) and DOE's Sandia National Laboratories successfully conducted three flight test campaigns in Tyler, Minnesota and Abilene and King Mountain, Texas, to assess eight proposed mitigation technologies for terminal- and long-range radars systems (Figure 3). The eight technologies included infill radar systems,[6] radar upgrades, and replacement radars.



	CARSR	ASR-11	ARSR-4
Range (nmi)	200	60	250
Scan Time (s)	12.0	4.8	12.0
Max Elevation (°)	20	30	30
Band	L	S	L

Figure 3 - IFT&E locations and tested program-of-record radar systems [8]

[6] Infill radar systems, also called augmentation radars, tend to have a shorter range and higher resolution than traditional radar systems and would be used to fill in the gaps in the surveillance area of the existing radar caused by wind turbines.

The first test in Tyler, Minnesota, was of a long-range Common Air Route Surveillance Radar (CARSR) and included the evaluation of three proposed mitigation technologies: the C Speed Lightwave[7] infill radar, the SRC LSTAR(V)3[8] infill radar, and a Raytheon CARSR processing upgrade.

The second test in Abilene, Texas, characterized the performance of the Airport Surveillance Radar (ASR-11) and evaluated two proposed mitigation technologies, the Terma Scanter 4002[9] infill radar, and a radar upgrade called the Booz Allen Hamilton RF Precision Nulling Device.

The third test in King Mountain, Texas, was at another long-range radar site, the Air Route Surveillance Radar (ARSR-4). The third test also evaluated three proposed mitigation technologies, a Lockheed Martin TPS-77[10] replacement radar, an Aveillant Holographic[11] infill radar, and a Raytheon X-band infill radar.

All the proposed mitigation technologies were impacted by wind turbines; however, many were significantly less affected than the existing program-of-record radars. Figure 4 summarizes the detection performance of the mitigation technologies by category and region. Because of the missions of many of these systems and their proprietary nature, many test results are considered Official Use Only and cannot be shared publicly. The results shown here were shared in a public version of the report [8], but did not include any Official Use Only information.

The data showed that the existing primary surveillance radars are impacted by wind turbines. In addition, while all systems tested were impacted by wind turbines, the replacement radar and most of the infill radars performed better than the existing primary surveillance radars in areas above wind turbines. “The infill radars demonstrated either sufficient, or near sufficient, detection performance, but elevated false alarm rates in general or poor detection performance for aircraft at higher elevation angles.” “The radar upgrades tested did not significantly improve the surveillance capability over wind farms, and therefore the technologies tested were not considered an effective mitigation. Nevertheless, data collected during the tests suggest alternative upgrade approaches that may be more successful; meaning this category of mitigation should not be altogether dismissed.” [8]

[7] https://www.cspeed.com/radar
[8] https://www.srcinc.com/products/radar/lstar-air-surveillance-radar.html
[9] https://www.terma.com/markets/ground/wind-farms/radar-mitigation/
[10] https://www.lockheedmartin.com/en-us/products/ground-based-air-surveillance-radars/tps-77.html
[11] https://www.aveillant.com/applications/windfarm-tolerant-radar/

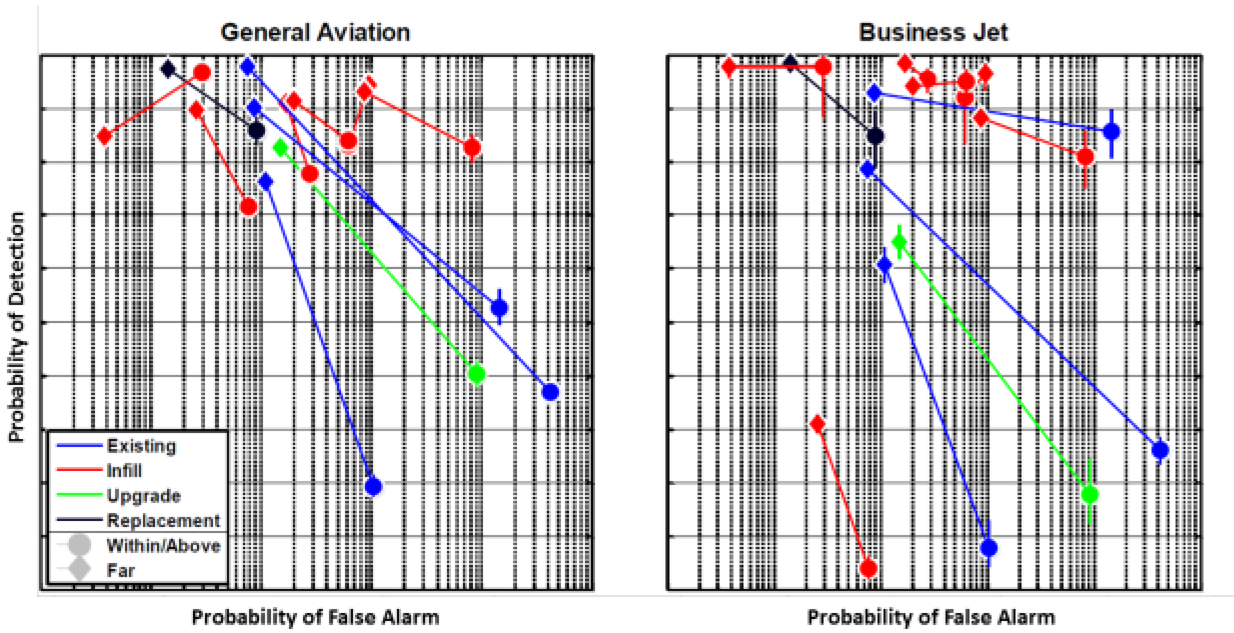


Figure 4 – These charts illustrate the performance of existing Federally owned radars and probability of detection and false alarm for various aircraft of different sizes using various mitigation technologies from IFT&E Report [8]. This shows the difference in performance of the tested existing radar systems and the mitigation technologies between areas above wind turbines, represented with a circle, and areas free of wind turbines, represented with a diamond. Better-performing technologies will have high probability of detection and low probability of false alarm and will be situated in the upper left corner of each graph. The line shows the difference in performance of the various systems in areas free of wind turbines versus areas above wind turbines.

The IFT&E campaigns were successful in increasing the technical understanding of the interference issues and the potential mitigation technologies, but they were only the beginning to bringing these solutions to market.

Under a memorandum of understanding[12] (MOU) signed in 2014, a consortium of Federal agencies comprising the DOD, DOE, FAA, and National Oceanic and Atmospheric Administration (NOAA) established the WTRIM working group to address the impacts of wind turbines on civilian and national defense radar system operations. The U.S. Department of Homeland Security (DHS) and Bureau of Ocean Energy Management (BOEM) have been observers of the WTRIM working group, with BOEM subsequently becoming a full participating member.

[12] https://www.acq.osd.mil/DODsc/library/15-S-1452%20WTRIM%20MOU.pdf

Through collaborative activities and coordinated investments, the WTRIM working group continues to fully address wind turbine radar interference as an impact to critical radar missions, ensure the long-term resilience of radar operations in the presence of wind turbines, and remove radar interference as an impediment to future wind energy development. DOE partners with multiple laboratories (Sandia National Laboratories, Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory, and MIT Lincoln Laboratory) that assist in these efforts.

The MOU established the framework of cooperation for the WTRIM working group to:

- Develop near- (5 years), mid- (10 years), and long-term (20 years) mitigation solution recommendations; and
- Determine funding requirements to implement workable solutions and include a process for each MOU participant to fund execution of specific near-, mid-, and long-term mitigation technologies.

To fulfill these goals, the WTRIM working group coordinates activities across three broad strategic themes [9]:

- Improving the capacity of the government and industry to evaluate the impacts of existing and planned wind energy installations on radar systems and their missions;
- Developing and facilitating the deployment of hardware and software mitigation measures to increase the resilience of existing radar systems to wind turbines; and
- Encouraging the development of next-generation radar systems that are resistant to wind turbine interference.

The WTRIM working group meets regularly to discuss and coordinate proposed research and field-testing activities in accordance with the MOU. In addition, the working group actively communicates with both the wind energy and radar industries to better understand any potential impacts from wind turbine development and solutions to their interference.

The WTRIM working group has recently engaged in the following activities:

- Provided critical resources and technical support, along with other Federal, state, and local partners, for a new series of aircraft test flights to collect data and evaluate potential mitigation technologies for air-defense radars near Brookings, South Dakota, in late August through early September 2021.
- Executed a new DOE-FAA interagency agreement in August 2021 to design and evaluate a prioritized set of radar software mitigation solutions for existing air traffic control and other radar systems under FAA's control [10].
- Led the renewal of a 5-year interagency agreement to continue the WTRIM working group to understand and reduce wind turbine interference with radar operations as an impediment to future wind energy development [11].

Each agency that voluntarily participates in the Wind Turbine Radar Interference Mitigation (WTRIM) working group receives its own annual appropriations and direction from Congress. Portions of these agencies' funds have been used to support agency-focused research, development, and demonstration of wind turbine radar interference mitigation activities. DOE's Wind Energy Technologies Office requested input from the Federal WTRIM working group on the status of past, current, and planned activities to reduce wind turbine impacts on civilian and defense radar systems.

In certain instances, DOD, DOE, FAA, DHS, NOAA, and BOEM have been able to provide resources for coordinated activities that support the missions of multiple agencies. Coordination among the agencies to advance, prioritize, and execute activities in support of the WTRIM working group's goals remains a voluntary effort under an interagency Memorandum of Understanding signed in 2014, which is under review for renewal at the time this report was prepared.

For a list of WTRIM working group agency offices see Appendix A - Wind Turbine Radar Interference Mitigation Working Group.

IV. Mitigation Option Status

This section summarizes and directly answers the requests from Congress regarding the status of testing, certification, and deployment of mitigation options by radar type and department or agency. This section and the following sections are organized by the mitigation categories as shown in Figure 5 and include the radar types and agency to which each mitigation can be applied.

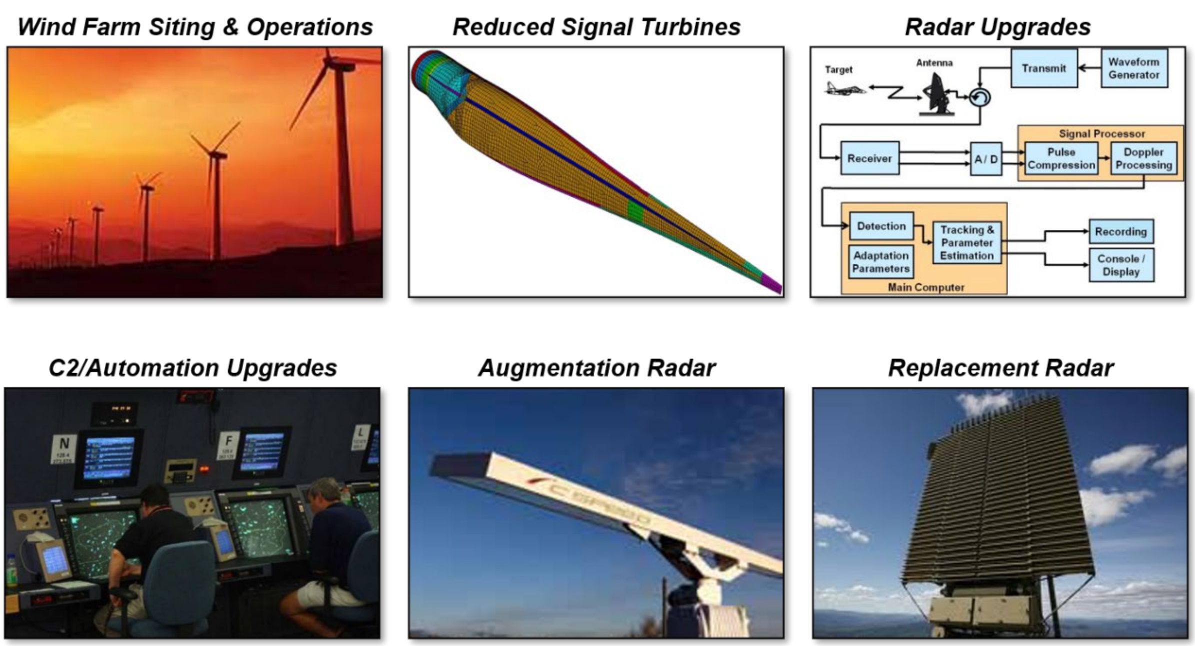


Figure 5 - Wind turbine radar interference mitigation technology categories [8]

Wind Farm Siting and Operations

Siting

The easiest and most-employed mitigation method is wind farm siting. This approach is when a developer modifies the specifics of the proposed wind farm in such a way that the wind turbines are out of the line-of-sight of the radar, or in less critical areas, as informed by the radar operator. Implementing this mitigation approach can be done by:

- Changing the size of the wind turbine (i.e., reducing the height)
- Removing wind turbines from the project
- Changing the location of wind turbines that fall within the line-of-sight of radar systems [12]
- Increasing the spacing between wind turbines

This mitigation approach applies to all types of radar systems except for coastal high-frequency radar systems. Coastal high-frequency radar systems require significant overlap of systems in the field and result in limited use of siting as a mitigation due to the number of coastal radar systems, which make it nearly impossible to move wind turbines to areas outside the coverage region of the radars [14]. While changing the location of wind turbines may be the easiest option, the growth of wind turbine deployment coupled with the many other facets of wind farm siting is making this option less viable. This is because much of the desired areas with good wind resources have already been developed and there is less room to build outside the coverage area of radar systems.

Siting and Analysis Tools

Federal agencies have developed tools that improve the existing capabilities that are used to site wind turbines and analyze their expected impacts on government radar systems. A few of the tools developed or improved upon by the WTRIM working group include:

- NOAA's NEXRAD Public Wind Turbine Siting Tool
- NOAA's NEXRAD Internal Wind Turbine Analysis Siting Tool
- The North American Aerospace Defense Command's Radar Obstruction Evaluation Model/Simulator
- DOD's Relocatable Over the Horizon Radar (ROTHR) WTRI Evaluation Mission Compatibility Analysis Tool
- DOD's Mission Compatibility Analysis Tool
- FAA's Windfarm Impact Tool (module within the radar toolbox)

Operations

Wind farm operational agreements have also been employed as a means of mitigating impacts to radar systems. Specifically, this can include using curtailment agreements so that the wind farm operator reduces the speed of the wind turbine blades during emergencies, such as for severe weather[13] or for scheduled military operations (e.g., launches or tests). DOD has entered into approximately 65 curtailment agreements but has not yet activated one for any emergency or event [16].

Reduced Signal Wind Turbines

Reducing the radar cross section of a wind turbine – the amount of energy a wind turbine reflects to the radar system – has been proposed as a mitigation solution for wind turbines that fall within the line-of-sight of radar systems. As a result, DOE has funded research [17] to investigate the feasibility of designing and manufacturing wind turbine blades with a reduced radar cross section that could be deployed within the line-of-sight of radar systems without any adverse impacts. The research found that integrating radar-absorbing material into the wind turbine blade manufacturing process could achieve a reduction in the radar cross section for a wind turbine blade, but that does not necessarily correspond to an equivalent reduction for the entire wind turbine. Significant work remains before altering wind turbines in this way can be considered a valid mitigation option. Additionally, the radar-absorbing material incorporated into the blade would need to be designed for the specific radar frequency or frequencies of interest.

Radar Upgrades

Radar upgrades can include improving the processing of the return signals from wind turbines to remove said signals from what a radar operator will see on the radar screen. This occurs within the existing radar computational processes and specifically affects detection and false alarm rates. These improvements may include modifying clutter maps,[14] constant false alarm rates,[15] or other filtering or preliminary tracking algorithms.

Command and Control (C2) and Automation Upgrades

Command and control and automation upgrades include upgrading the process at the automation system (e.g., the Standard Terminal Automation Replacement System, Standard Terminal Automation Replacement System (STARS)[16], or the Air and Marine Operations Surveillance System,[17] and the Battle Control System-Fixed).

Generally, a command-and-control-type mitigation improves the tracking logic and performance of a command-and-control system based on the radar's target detection. One

[13] An example of a National Weather Service curtailment agreement can be found online: https://www.windaction.org/posts/43184-nextera-letter-of-intent-wind-turbine-operational-curtailment-during-severe-weather

[14] Clutter maps are created in the radar processor and are a tool used in target tracking algorithms to account for stationary clutter.

[15] Constant false alarm rates are part of the radar system's algorithm used to adjust the detection of targets in the presence of background signal noise.

[16] https://www.faa.gov/air_traffic/technology/tamr/arts/

[17] https://www.dhs.gov/publication/air-and-marine-operations-surveillance-system

example is improving the fusion process between different radars viewing the same air space, thereby potentially allowing nonimpacted radar to surveil the airspace of an impacted radar.

Augmentation Radars

The use of augmentation radars, also called infill radars, would add radars in or around wind farms to make up for lost coverage of the existing impacted radar. These radars tend to have a shorter range and higher resolution with the intention of tracking targets in areas that would be lost to the existing radar.

The WTRIM working group has tested infill radars at multiple sites across the country including during the IFT&E [8] and at Travis Air Force Base [19]. The project at Travis Air Force Base built upon the previous testing of the infill radar systems and researched the use of these radars to recover lost air space for an Airport Surveillance Radar (ASR-11[18]) or Digital Airport Surveillance Radar (DASR). This project not only attempted to quantify the performance of the infill radar in the airspace above wind turbines, but it also investigated the process and challenges with integrating infill radar data into the command-and-control automation, in this case, STARS. The following two main conclusions came out of this project:

1. Infills show less clutter and result in better performance than the DASR above-wind turbines.
2. Additional improvements for using infill radars to mitigate wind turbine interference might be achieved as integration with the automation platforms evolves.

These projects have demonstrated that infill radars can serve as a viable mitigation solution for impacted radar systems. However, before they can be deployed into the National Airspace System (NAS) and used by the FAA, they must undergo a validation and certification process controlled by the FAA. The FAA is currently working to determine, define, and validate the necessary processes to qualify nonfederal radars (infill radars) for use in the NAS.

Replacement Radars

These systems replace existing, less-sophisticated radars with more-advanced radars, typically phased-array radars with narrow three-dimensional beams with higher resolution and advanced clutter mitigation capabilities. They could be placed at current radar sites, or at alternative, more desirable locations. For example, a replacement radar, a Lockheed Martin TPS-77[19] long-range radar, was tested during the 2013 IFT&E at King Mountain, Texas. As shown in Figure 4, the replacement radar performed significantly better than the existing radar systems in areas above wind turbines.

[18] https://www.faa.gov/air_traffic/technology/asr-11/

[19] https://www.lockheedmartin.com/en-us/products/ground-based-air-surveillance-radars/tps-77.html

Spectrum Efficient National Surveillance Radar
The Spectrum Efficient National Surveillance Radar (SENSR) [20] program, consisting of the FAA, DOD, DHS, and NOAA, was initiated to determine the feasibility of reducing the size of the L-Band radio frequency used by government radar systems and using the resulting funding from the sale of that bandwidth to replace the aging legacy radar systems with a single system. As a result, the program hoped to reduce the maintenance footprint and related supply chains as well as address growing issues, such as resolving the barrier to wind deployment driven by wind turbine radar interference concerns.

Airspace Non-Cooperative Surveillance Radar
The Airspace Non-Cooperative Surveillance Radar (ANSR) program [21] is a FAA and DOD initiative launched in 2022 to addresses non-cooperative radar systems (ASRs and DASRs) that have surpassed or will soon surpass their service life. This program will focus on component replacement, subsystem replacement, or full-system replacement. The FAA plans to replace non-cooperative radar systems or components starting in 2024.

V. Remaining Work and Resource Gaps for Mitigations Currently Being Developed

This section summarizes the status of mitigation options currently being developed and tested as well as the cognizant agencies. To be deployable means the mitigation option is available, either commercially or as government-furnished equipment, and proven to mitigate wind turbine interference for a specific radar system or systems. Options being developed or tested today span several radar types and systems. For consistency and to reduce redundancy, the current mitigation option work projects being funded are addressed in the remainder of this section under the same categories noted in Section IV.

Wind Farm Siting and Operations

Siting and Analysis Tools
These projects improve user friendliness, increase database utility, improve effectiveness of modeling capabilities, and extend usefulness for all stakeholders concerned with reducing wind turbine radar interference. Each new enhancement has continued the move toward eliminating wind turbine radar interference as a barrier to renewable energy system deployment.

U.S. Wind Turbine Database

DOE's Lawrence Berkeley National Laboratory (LBNL), in partnership with the United States Geological Survey and American Clean Power, has developed and maintains the U.S. Wind Turbine Database (USWTDB).[20]. The database provides locations and technical specifications for all known existing utility-scale wind turbines in the United States. It covers both land-based and

[20] https://eerscmap.usgs.gov/uswtdb/

offshore wind energy projects. WTRIM stakeholders requested a separate database of offshore wind energy development due to the rapid growth expected and the need to incorporate additional sources of information to determine the potential wind turbine radar interference impacts of wind energy operations offshore. LBNL and BOEM recently developed the U.S. Wind Turbine Project Pipeline, which includes a complete data set of proposed, but not yet built, offshore wind turbines.

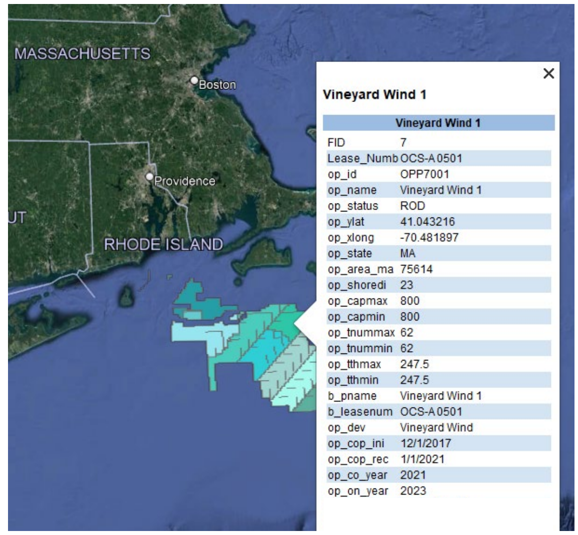


Figure 6 - Sample graphic from the new U.S. Wind Turbine Project Pipeline database capability

A sample graphic is shown in Figure 6. The database of offshore wind projects is current as of January 2022, and LBNL is working with BOEM to build a system for regular updates [22].

Enhancement of the ASR-11 Radar Toolbox To Improve Existing Capabilities as a Mitigation

The FAA is undertaking new ASR-11 Radar Toolbox enhancements that are expected to improve both target and weather processing capabilities of the ASR-11 Radar Toolbox. These capabilities can be customized over wind farms by making specific adjustments to radar maps, such as additions of wind turbine locations. New modeling tools are needed to take advantage of improved and existing ASR-11 capabilities.

As of May 2022, the FAA added a feature to their maps to remove wind turbine clutter (using weather Range-Azimuth Gates) [23]. In parallel, the FAA performed additional tool updates for Build 14 (a project noted later in this section) to minimize costs across the spectrum of the ASR-11's mission requirements. An enhanced Radar Toolbox was released within the FAA in FY22 and it remains under active development.

Relocatable Over the Horizon Radar Wind Turbine Radar Interference Evaluation Mission Compatibility Analysis Tool

DOD's ROTHR system provides wide-area air and sea surveillance track information to support U.S. Southern Command's Counter-Illicit Drug Trafficking Mission. The ROTHR Modeling and Simulation Tool is a key component of the Wind Farm Modeling Process, as the analysis it provides spans both land-based and offshore wind energy farms [24]. The tool currently requires a close collaborative process between MIT LL and the U.S. Navy's Forces Surveillance Support Center (FSSC). This project currently comprises several phases of transitioning the tool to FSSC and will end with the Center becoming the main operator of the modeling system as new graphical user interface capabilities are developed and transitioned to the Virginia FSSC team's offices.

MIT LL is jointly performing studies and concurrently developing graphical user interfaces for the ROTHR analysis tool. Expected project completion is the last quarter of FY23.

Reduced Signal Wind Turbines

WTRIM agencies are not currently funding any projects to develop wind turbines with reduced radar interference, but they remain open to funding promising work in this area in the future.

Radar Upgrades

Deployment of Stationary Doppler Target Suppressor Code on ASR-11

This is a follow-on project stemming from an FAA success story regarding the CARSR 270 Upgrade[21] and was initiated after findings were reviewed from the first IFT&E event conducted at the radar site near Tyler, Minnesota. The project comprises the following two core tasks:

1. Evaluate Stationary Doppler Target Suppressor (SDTS) code on ASR-11 hardware. This task involves conducting an engineering analysis regarding the addition of new algorithms such as the FAA-developed SDTS originally designed for and currently deployed in Common Air Route Surveillance Radars to existing ASR-11/DASR digital signal processing.

   The SDTS software has been integrated and is running in the ASR-11 Support Lab.

2. Optimize SDTS for ASR-11 sites. This study uses multiple versions of adaptation settings to explore the effects of those adaptations on the radar picture. The project uses the ASR-11 simulator with SDTS software to process radar return data from sites with wind turbine interference. The resulting report provides recommendations for optimization of the SDTS code at a typical radar site.

Adjustments to SDTS parameters continue to be made and previously collected flight data are being reprocessed. The results are being collected for further analysis. [23].

Next-Generation Weather Radar Algorithm Study

This project focuses on a software improvement for weather radars. DOD is working with Georgia Tech Research Institute on an algorithm to work in conjunction with ground clutter filter to aid in separating wind turbine interference from weather.

The program is funded and is expected to be completed in early 2023. If the algorithm proves viable, the findings will be presented to a NEXRAD peer review board that will then determine

[21] NOTE: This software is installed at all CARSR radar sites, although each individual CARSR system requires configuration and optimization for each wind turbine project that impacts the individual radar [16].

the mitigation value versus the cost and risk of using the algorithm and integrating it into the NEXRAD system's operational software [16].

Least Squares Wind Turbine Suppression Algorithm

This is a software improvement project for airport surveillance radars. DOD is working with Space Dynamic Laboratory on a new algorithm to mitigate wind turbines' observed effects on radar systems by a process that removes wind turbine clutter to improve the radars' ability to perform its mission in or above areas with wind turbines.

This is project is currently funded to test, characterize, and optimize the algorithm. If successful, deployment of the algorithm will require the FAA to test, evaluate, and integrate it into airport surveillance radar software; the project is expected to take approximately 3−5 years to complete [16].

Implementation of Mitigation for Offshore Wind Turbine Interference on Coastal Oceanographic Radar Systems

Managed by NOAA, there are currently 160 coastal surface high-frequency radars in the U.S. Integrated Ocean Observing System (IOOS) network measuring ocean current velocities and waves in near-real time. Their range extends out beyond 150+ kilometers offshore with a base resolution of 0.2–6 kilometers. A core mission for the high-frequency radars is public safety. Surface current measurements available without these devices is a mere 300 measurements per hour from in situ methods (e.g., moored buoys). However, with high-frequency radars, there are some 100,000+ measurements per hour benefiting weather, ocean currents, and search and rescue efforts.

This work is funded by BOEM using the Coastal Ocean Dynamics Applications Radar (CODAR), a high-frequency-radar system. This project implements a real-time software solution to minimize wind turbine interference.

A new tool to simulate offshore wind turbine interference on coastal high-frequency radars will be developed based on the buildout of offshore wind farms [26].

Software Tools to Mitigate Wind Turbine Interference in the U.S. IOOS Network

This project is funded by the NOAA Integrated Ocean Observing System Ocean Technology Transition program. Partners include the Woods Hole Oceanographic Institution, University of California Santa Barbara, CODAR Ocean Sensors, Ltd., and Rutgers University. The objectives include:

- Documenting the best practices for high-frequency-radar setup that minimize interference
- Setting up robust WTRIM tests and testing standards

- Generating a three-tiered testing data set including fully simulated data, simulated wind turbine interference radar data added to SeaSonde® spectra, and SeaSonde® data collected from sites near wind farms paired with wind turbine rotation rates
- Fully testing the mitigation software developed under BOEM
- Performing a field study of the impacts from wind turbine interference [27].

Oceanographic High-Frequency-Radar Data Preservation in Wind Turbine Interference Mitigation

Funded by the National Offshore Wind Research and Development Consortium, this project includes the following partners: CODAR Ocean Sensors, Ltd., Old Dominion University, Rutgers University, and East Carolina University. This project is using multiple high-frequency radars to fill in gaps from the wind turbine radar interference and will implement a machine-learning model to identify and separate the wind turbine interference from the sea echo [28].

Command and Control and Automation Upgrades

Determine the Value of New Wind Turbine Radar Interference Mitigation Features for the ASR-11 Build 14 upgrade

This FAA project is designed to determine if there are WTRIM-related benefits of including both Weather (Wx) Edge Tagging and increased Range-Azimuth Gate (RAG) count in ASR-11 Software Build 14 as a mitigation solution. Previous United States Air Force data analysis suggests that disabling the ASR-11 Wx Edge Tag functionality over areas like the Wind Resource Area near Travis Air Force Base, California, could improve the aircraft tracking. In addition, it is known that adding more RAGs to the ASR-11 software can allow for more precise removal of wind turbines from target processing by increasing the resolution of the radar. This project is designed to address the inclusion of Wx Edge Tagging functionality and increased RAG count in ASR-11 Software Build 14 and test these new features at an operational site.

The FAA team finalized development test procedures in May 2022. A Build 14 development test in progress and an operational test is being tentatively scheduled for the first or second quarter of FY23 [23].

Augmentation Radar

Infill Radar as a Mitigation (Applicable to NAS Terminal and Long-Range Radar Systems)

The IFT&E program and WTRIM working group have conducted several field tests of infill radars. The results of these field tests led to the Travis Air Force Base Pilot Mitigation Project and a field test, funded in part by DOD, DOE, and the FAA, which was designed to incorporate the raw radar data from two commercial infill systems into an impacted Airport Surveillance Radar through the STARS air traffic control display. The infill systems demonstrated their ability to successfully detect aircraft, track performance, and integrate with the local radar. The project concluded that the results, while not acceptable for immediate acquisition and inclusion as a mitigation technology into the NAS, did show potential to mitigate wind turbine interference [19]. Field testing of the initial approach was completed in January 2022.

The conclusion of the recent field tests led to an infill radar integration approach whereby the FAA is working in the lab to improve the overall performance between the Airport Surveillance Radar, infill radars, and STARS [19]. As of the writing of this report, the validation process is expected to lead to an approved infill radar certification process in 2023.

Airport Surveillance Radar/Air Route Surveillance Radar Multi-static Prototyping Effort

The DOD Siting Clearinghouse funded a feasibility study in 2021 regarding the development of a multi-static receiver augmentation system to reduce the effects of wind-turbine-induced radar interference on CARSR, ARSR-4, and ASR-11/DASR radar systems.

The follow-on to that study, co-funded by DOE, DOD, and BOEM, is a project that is currently being pursued as both a software and hardware improvement system for Airport and Air Route Surveillance Radars. MIT LL has been tasked with developing low-cost receivers to deploy around wind farms to improve sensitivity, increase resolution, reject clutter from wind turbines, and can operate continuously across a range of environmental conditions.

This study is partially funded to begin algorithm development, multi-sensor analysis, and conduct an operational evaluation. If testing is successful, the radar industry will be able to review the prototype software and hardware design. The expectation would be that a manufacturer could produce the system in sufficient quantities for deployment at multiple radar sites and wind farms over time. In addition, the system will require FAA certification for integration with the National Airspace System [16].

Replacement Radar

Passive Radar System

DOD and DHS have committed to testing passive radar systems for Airport and Air Route Surveillance radars and have recently studied or field tested several versions. These systems may provide an adequate performance capability to meet some limited DOD and DHS mission requirements. A passive radar could potentially be used in non-air-traffic-control environments (for example, homeland defense/security missions) immediately. Additionally, these systems may also be used to enhance air traffic control situational awareness prior to FAA certification.

Data collected from recent field tests are being analyzed by MIT LL who is expected to develop a final classified report in FY23 [16].

Multi-Function Phased-Array Radar

Funded by DOE, MIT LL is coordinating with the NOAA National Severe Storms Laboratory to demonstrate the capabilities of next-generation radar systems required to operate in modern wind turbine environments by leveraging the panel-based phased array radar technology that

MIT LL has developed via the NOAA and FAA jointly funded multi-function phased-array radar (MPAR) program.

MIT LL is assessing the suitability of the MPAR 10-panel demonstrator hardware, MPAR Advanced Technology Demonstrator system in Norman, Oklahoma, and other tile-based phased-array panel technology for relevant aircraft, weather, and atmospheric science measurements in wind turbine environments [30].

For Table 1, the following definitions and caveats apply:

- Remaining Steps for Mitigation Deployment: Depending on the TRL of each project, the remaining steps to deploy the mitigation technology may fall outside the current scope of the R&D project.
- Target deployment timeline is defined as:
  - Near term (1−3 years)
  - Mid term (4−9 years)
  - Long term (10 years and beyond).

Resource Gaps for Mitigation Deployment: Depending on the TRL of each project, deployment of the mitigation technology may fall outside the scope of the R&D project. Potential gaps are identified below.

Table 1 - Table of Mitigations Currently Being Developed or Tested and Including Resource Gaps

Mitigation	Applicable Radar Type	Tool or Radar Owner and/ or User	Current Status[22]	Remaining Steps for Mitigation Deployment	Target Deployment	Resource Gaps for Mitigation Solution Deployment	Agency Mitigation Sponsor(s)
Wind Farm Siting and Wind Turbine Radar Interference Analysis Tools							
U.S. Wind Turbine Database [22]	NA	DOE, USGS, FAA, BOEM	In use Project pipeline updates now include pending land-based and offshore wind energy developments	Updating and validating offshore wind data fields	Near term	No	DOE

[22] As of September 2022

Mitigation	Applicable Radar Type	Tool or Radar Owner and/ or User	Current Status[22]	Remaining Steps for Mitigation Deployment	Target Deployment	Resource Gaps for Mitigation Solution Deployment	Agency Mitigation Sponsor(s)
ASR-11 Radar Toolbox Enhancements [23]	ASR-11 and DASR	FAA, DOD	Additional tool updates for Build 14 are being performed to minimize costs	Implementing adjacent target RAG cell merge; Radar toolbox testing and reporting	Near term	No	FAA
Relocatable Over-the-Horizon Radar (ROTHR) Wind Turbine Radar Interference Evaluation Mission Compatibility Analysis Tool [24]	ROTHR	DOD	MIT LL is jointly performing studies with the FSSC team and concurrently developing a user interface for the ROTHR analysis tool	Performing additional studies for the ROTHR analysis tool	Near term	Yes	DOD
Reduced Signal Wind Turbines							
No projects in this category are currently funded.							
Radar Upgrades							

Mitigation	Applicable Radar Type	Tool or Radar Owner and/ or User	Current Status[22]	Remaining Steps for Mitigation Deployment	Target Deployment	Resource Gaps for Mitigation Solution Deployment	Agency Mitigation Sponsor(s)
Next Generation Weather Radar (NEXRAD) Algorithm Study [16]	NEXRAD	NOAA, FAA, DOD	Georgia Tech Research Institute is developing an algorithm, in conjunction with a ground clutter filter to help separate wind turbine interference from weather	Algorithm testing and NEXRAD peer review needed to determine the mitigation value vs. cost/risk factors	Near term	Yes	DOD
Least Squares Wind Turbine Suppression Algorithm [16]	ASR-11, DASR, CARSR	DOD, FAA	The Space Dynamic Laboratory is developing a new algorithm to mitigate observed wind turbine effects on radar systems using a process to remove wind turbine signatures to improve the radars' ability to perform its mission	Testing, characterization, and optimization of the algorithm is required. If successful, the FAA will need to test, evaluate, and integrate the algorithm into NAS software	Mid term	Yes	DOD

Mitigation	Applicable Radar Type	Tool or Radar Owner and/ or User	Current Status[22]	Remaining Steps for Mitigation Deployment	Target Deployment	Resource Gaps for Mitigation Solution Deployment	Agency Mitigation Sponsor(s)
Implementation of Mitigation for Offshore Wind Turbine Interference on High-Frequency Coastal Oceanographic Radar [26]	CODAR SeaSonde® Oceanographic HF radars	NOAA IOOS Regional Association member universities	This project concluded in Dec. 2021 by coding and documenting a real-time software program that mitigates offshore wind turbine interference by using signal processing to discard turbine-polluted data along with optimizations to the sweep rate and Doppler settings of the SeaSonde® HF-radar	Installing and field testing this new software tool in SeaSonde® HF radars that have offshore wind farms within their area of measurement coverage, once such large-scale offshore wind farms are built	TBD based on the buildout of offshore wind farms	No	BOEM
Software Tools for the Mitigation of Wind Turbine Interference in the U.S. IOOS Network [27]	CODAR SeaSonde® Oceanographic HF radars	NOAA IOOS Regional Association member universities	The objectives of this continuing project include documenting the best practices for high-frequency-radar setup that minimize interference, setting up robust WTRIM tests and testing standards	Testing the mitigation software and performing a field study of wind turbine interference impacts	TBD based on the buildout of offshore wind farms	Yes	NOAA
Oceanographic High-Frequency Radar Data Preservation in Wind Turbine Interference Mitigation [28]	CODAR SeaSonde® Oceanographic HF radars	NOAA IOOS Regional Association member universities	This project currently uses multiple high-frequency radars operating bi-statically to fill in gaps from wind turbine radar interference	Implementing a machine-learning model to identify and separate the wind turbine interference from the sea echo	TBD based on the buildout of offshore wind farms	No	National Offshore Wind Research and Development Consortium

Mitigation	Applicable Radar Type	Tool or Radar Owner and/ or User	Current Status[22]	Remaining Steps for Mitigation Deployment	Target Deployment	Resource Gaps for Mitigation Solution Deployment	Agency Mitigation Sponsor(s)
Command and Control and Automation Upgrades							
ASR-11 Build 14 Enhancement with Weather Edge Tagging and Increased RAG Count [23]	ASR-11, DASR	FAA, DOD	Development of test procedures are complete	Installation at Travis Air Force Base, operational testing, documentation updates, determination of WTRIM features	Near term	Yes	FAA, DOE
Augmentation Radar							
Infill Radars [19]	ASRs, ARSRs, CARSR	FAA, DOD	FAA is validating an infill radar integration approach that is expected to lead to a certification process. Field testing of this approach was completed in January 2022	Final validation reporting, and certification process development	Near term	Yes	FAA
ASR/ARSR Multi-static Prototyping Effort [16]	ASRs, ARSRs	FAA, DOD	Modeling analysis, hardware development, and initial data collection are complete	Algorithm development, multi-sensor analysis, final array design, operational evaluation and FAA certification	Mid term	Yes	DOD, DOE, BOEM
Radar Replacement							

Mitigation	Applicable Radar Type	Tool or Radar Owner and/ or User	Current Status[22]	Remaining Steps for Mitigation Deployment	Target Deployment	Resource Gaps for Mitigation Solution Deployment	Agency Mitigation Sponsor(s)
Multi-Function Phased-Array Radar (MPAR) [30]	NEXRAD, WSR-88	NOAA	MIT LL is assessing the MPAR for relevant aircraft, weather, and atmospheric science measurements in wind turbine environments.	Demonstration, analysis, and assessment	Mid term	Yes	DOE
ANSR [21]	ASRs	FAA, DOD	The FAA and DOD have determined the ASR-11 requirements will be the baseline for the ANSR project	The FAA and DOD will establish cost share and this program should be formally established in FY24	Mid to long term	Yes	FAA

VI. Mitigations Not Being Considered Because of Resource Constraints

This section lists mitigation options that are not currently being considered because of resource constraints but may be promising with additional resources and prioritization. The list is presented in Table 2 according to mitigation category.

Table 2 - Mitigations Not Being Considered Due to Resource Constraints

Mitigation	Radar Type	Radar Owner or Operator	Project Description
Wind Farm Siting and Wind Turbine Radar Interference Analysis Tools			
None			
Reduced Signal Wind Turbines			
Wind Turbine Lightning Mitigation System Radar Cross Section Reduction [31]	Potentially applies to multiple radar system types	Varies by radar type	- A previous report, noted in Table 3, investigated proposed modifications to lightning mitigation cables to reduce the radar cross section when illuminated by ROTHR systems, which operate in the high-frequency band (3–30 megahertz). An expanded study that addresses specific frequencies used in ASR and ARSR systems versus the range of frequencies studied in the study for ROTHR (which varies frequency based on environmental conditions) could prove more cost-effective in developing a successful change to the lightning mitigation system installed in wind turbines - Two examples from the studies include breaking up lightning mitigation system cables using spark gap connections and changing the orientation of the cable within the wind turbine blade or expanding the study to include both simulated and measured analyses of radar cross section mitigation techniques. In addition, there were several recommendations on further research that could prove valuable based on the scope and duration of wind farm deployments both on land and offshore expected over the next 10 years or more
Radar Upgrades			
Airport Surveillance Radar Wind Farm Mitigation [16]	Applies to ASR-11 and DASR systems	FAA, DOD	This proposed project is both a software and hardware upgrade to Airport Surveillance Radars (ASR-11) and Digital Airport Surveillance Radars (DASR). The objective is to increase the signal processing capability and modify the software that reduces wind turbine radar interference effects. The study portion would address parts obsolescence including redesign, development, and testing of various components
Command and Control and Automation Upgrades			

Mitigation	Radar Type	Radar Owner or Operator	Project Description
None			
Augmentation Radar			
Field Test of Multi-Static Radars [29]	Potentially applies to all ASR and ARSR system types	FAA, DOD	Previous field tests showed that only one of the two multi-static systems tested to date met DOD and FAA requirements. Additional research, development, and testing focused on multi-static radars will answer two remaining issues of concern: 1. Current production of the successful multi-static radar is focused on filling a higher national security requirement 2. It will require hardware and software modifications to be made compatible with the current National Air Space configuration
Replacement Radar			
Three-Dimensional Pencil Beam Long-Range Radar System [8]	Potentially applies to all ASR and ARSR system types	Varies by radar type to be replaced	The TPS-77 radar is an actively electronically scanned phased-array radar that could be used in a way that avoids wind turbines being visible to the radar. This radar performed better than the existing program-of-record radars and from a technical performance standpoint, could have been the nearest-term mitigation option. [8]

VII. Dismissed Mitigations With Reasoning

This section provides a summary of mitigation options that have been dismissed as well as an explanation as to why they are not considered viable. Table 3 highlights these options according to mitigation category.

Table 3 - Dismissed Mitigations With Reasoning

Mitigation	Radar Type	Radar Owner or Operator	Project Description	Reasons for Dismissal
Wind Farm Siting and Operations				
NOAA IOOS - Siting as a Mitigation Option for High-	Applies to high-frequency coastal radar systems	NOAA	NOAA IOOS performed an internal study to determine if siting could be a viable option for mitigating wind-turbine-induced interference along the coastlines of the continental United States	The results of the study determined that siting is not effective in the coastal high-

Mitigation	Radar Type	Radar Owner or Operator	Project Description	Reasons for Dismissal
Frequency Radars [13]				frequency arena primarily due to the complexity of sensor overlap.
		Wind Turbines with Reduced Radar Interference		
Incorporation of Radar-Absorbing Material into Wind Turbine Blades [17]	Applies to ASR, ARSR, NEXRAD, and ROTHR systems	Varies by radar type	DOE funded this research to investigate the feasibility of designing and manufacturing wind turbine blades with a reduced radar cross section that could be deployed within the line of sight of radar systems without any adverse impacts. The radar-cross-section-reduction structures were intended for direct integration into the wind turbine blade with minimal cost and performance impacts. The research found that integrating radar-absorbing material into the wind turbine blade manufacturing process could achieve a reduction in the radar cross section for a wind turbine blade but that does not necessarily correspond to an equivalent reduction for the entire wind turbine. Significant work remains before altering wind turbines in this way can be considered a valid mitigation option. Additionally, the radar-absorbing material incorporated into the blade will need to be designed for the specific radar frequency or frequencies of interest.	The report noted that significant work remained before any reduced radar-cross-section wind turbine can be considered a valid mitigation option No further DOE funding of this project is in progress due to the industry activities regarding stealth coatings for wind turbine blades[23]
Modification to Wind Turbine Blade Lightning Mitigation System [31]	Potentially applies to multiple radar system types – investigated for ROTHR	Varies by radar type	DOE funded this research to investigate proposed modifications to lightning mitigation system cables to reduce the radar cross section when illuminated by ROTHR systems that operate in the high-frequency band (3–30 megahertz). Simulated analyses of the modifications and further research recommendations were provided	The simulation showed promise for radar-cross-section reduction at specific frequencies but determined that this was not a feasible option for the ROTHR system that adjusts its frequency based on atmospheric conditions

[23] https://www.qinetiq.com/en/what-we-do/services-and-products/stealth-wind-turbines

Mitigation	Radar Type	Radar Owner or Operator	Project Description	Reasons for Dismissal
		Radar Upgrades		
Deployment of SDTS Code on ASR-11s [23]	ASR-11 and DASR	FAA, DOD	DOE funded FAA to apply the SDTS algorithm (which had been successfully applied to CARSRs) to a different radar type. FAA completed optimization and testing of code on a newly developed and validated ASR-11 simulator and verified that sufficient computing resources exist on the platform for the SDTS algorithm	The SDTS algorithm was detrimental to ASR-11 performance across various parameter optimizations. The ASR-11 simulator developed under this project remains a useful asset to quickly test new mitigation algorithms
Radio Frequency Precision Nulling Device [32]	ASR-11	FAA	This concept was designed to be attached to the radar to create a deep shadow to minimize energy reflected from the wind turbines to the radar	While this concept did provide some attenuation from the wind turbines, it was not sufficient to mitigate the false alarms. Also, it created a large shadow extending beyond the wind turbines which negatively impacted the performance of the radar in this airspace
		Radar Replacement		
Spectrum Efficient National Radar (SENSR) [20]	Potentially applies to all ASR and ARSR system types	FAA, DOD, DHS	The FAA, DOD, and DHS were mandated to examine the feasibility of making 50 megahertz of the spectrum available within 1,300-1,350 megahertz, with the aim of identifying potential surveillance solutions and evaluating the capability to sell off this band of the spectrum	The study found that it is not feasible to vacate the frequency range and the SENSR agencies submitted letters of nonconcurrence with the auction to the National Telecommunications and Information Administration

VIII. References

[1] R. Wiser, M. Bolinger, B. Hoen, D. Millstein, J. Rand, G. Barbose, N. Darghouth, W. Gorman, S. Jeong and B. Paulos, "Land-Based Wind Market Report: 2022 Edition," 2022. [Online]. Available: https://www.energy.gov/sites/default/files/2022-08/land_based_wind_market_report_2202.pdf. [Accessed 16 September 2023].

[2] W. Musial, P. Spitsen, P. Duffy, P. Beiter, M. Marquis, R. Hammond and M. Shields, "Offshore Wind Market Report: 2022 Edition," 2022. [Online]. Available: https://www.energy.gov/sites/default/files/2022-09/offshore-wind-market-report-2022-v2.pdf. [Accessed 16 September 2023].

[3] P. Gilman, "Activity Area Overview Presentation: Regulatory & Siting," 2 August 2021. [Online]. Available: https://www.energy.gov/sites/default/files/2021-10/fy21peerreview-regulatoryandsiting-gilman.pdf. [Accessed 19 January 2023].

[4] Federal Aviation Administration, "Air Traffic Control / Surveillance Systems," Federal Aviation Administration, [Online]. Available: https://www.faa.gov/air_traffic/publications/atpubs/aim_html/chap4_section_5.html. [Accessed 19 August 2022].

[5] Integrated Ocean Observing System, "HF Radar," National Oceanic and Atmospheric Administration, [Online]. Available: https://ioos.noaa.gov/project/hf-radar/#:~:text=About%20HF%20Radar,from%20one%20location%20to%20another.. [Accessed 19 August 2022].

[6] Federation of American Scientists, "AN/TPS-71 ROTHR (Relocatable Over-the-Horizon Radar)," Federation of American Scientists, 29 June 1999. [Online]. Available: https://nuke.fas.org/guide/usa/airdef/an-tps-71.htm. [Accessed 19 January 2023].

[7] National Oceanic and Atmospheric Adminstration Radar Operations Center, "NEXRAD Technical Information," FAA, 22 July 2022. [Online]. Available: https://www.roc.noaa.gov/WSR88D/Engineering/NEXRADTechInfo.aspx. [Accessed 19 August 2022].

[8] B. Karlson, B. LeBlanc, D. Minster, D. Estill, B. Miller, F. Busse, C. Keck, J. Sullivan, D. Brigada, L. Parker, R. Younger and J. Biddle, "IFT&E Industry Report Wind Turbine-Radar Interference Test Summary," Sandia National Laboratories, Albuquerque, NM, 2014.

[9] P. Gilman, L. Husser, B. Miller and L. Peterson, "Federal Interagency Wind Turbine Radar Interference Mitigation Strategy," US Department of Energy, Washington, DC, 2016.

[10] U.S. Department of Energy, 15 June 2021. [Online]. Available: https://www.energy.gov/eere/wind/articles/doe-partners-interagency-agreements-avoid-potential-impacts-radar-systems-wind. [Accessed 17 September 2023].

[11] Department of Defense, Department of Energy, Federal Aviation Administration, National Oceanic and Atmospheric Administration, Bureau of Ocean Energy Management, *Memorandum of Agreement Establishment of the Wind Turbine Radar Interference*

Mitigation Working Group, Washington, DC: https://windexchange.energy.gov/projects/radar-interference-working-group, 2023.

[12] D. J. Brigada and J. Ryvkina, "Radar-Optimized Wind Turbine Siting," IEEE Transactions on Sustainable Energy, Lexington, 2022.

[13] National Oceanic and Atmospheric Administration Integration Ocean Observing Systems, *Version 1 of WTRIM Software for HFR: Deliverables from 2nd BOEM-funded WTRIM Study by CODAR Ocean Sensors, Ltd. for NOAA IOOS's HFR National Network,* Washington, DC, 2022.

[14] A. Kirincich, D. Cahl, B. Emery, M. Kosro, H. Roarty, D. Trockel, L. Washburn and C. Whelan, "High Frequency Radar Wind Turbine Interference Community Working Group Report," June 2019. [Online]. Available: https://darchive.mblwhoilibrary.org/entities/publication/c01f9113-0d0b-518f-8bdd-3f46e5fcd1db. [Accessed 17 September 2023].

[15] R. Colburn, C. Drummond, M. Miles, F. Brody, C. McGillen, A. Krieger and R. Jankowski, "Radar Interference Analysis for Renewable Energy Facilities on the Atlantic Outer Continental Shelf," Bureau of Ocean Energy Management, Washington, DC, 2020.

[16] Department of Defense, *Briefing to the Senate Armed Services Commitee on Military Aviation and Installation Assurance Clearinghouse Matters (sec. 313 of SASC Committee Report 117-39),* Washington, DC, 2022.

[17] 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. Loui, "Radar-Cross-Section Reduction of Wind Turbines (Part 1)," Sandia National Laboratories, Albuquerque, NM, 2012.

[18] B. Miller, "Travis Air Force Base Pilot Mitigation Project Summary Report for Public Release," 2021.

[19] B. Karlson and B. E. Miller, "Wind Turbine Interference on Radar Systems; Travis Air Force Base Pilot Mitigation Project," in *AWEA Siting and Environmental Compliance Conference*, Washington, DC, 2020.

[20] U.S. Department of Commerce, "Annual Report on the Status of Spectrum Repurposing and Other Initiatives," 2023. [Online]. Available: https://ntia.gov/sites/default/files/publications/annual_spectrum_repurposing_initiatives_report_final.pdf. [Accessed 18 August 2023].

[21] Air Force Flight Standards Agency, *Airspace Non-Cooperative Radar (ANSR) Informational Briefing,* Oklahoma City, 2022.

[22] B. Hoen and J. Rand, *US Offshore Wind Project Pipeline Database Briefing,* Berkley: Lawrence Berkley National Laboratory, 2022.

[23] S. Mach, *FAA WTRIM Project Status May 2022,* Washington, DC: Federal Aviation Administration, 2022.

[24] Forces Surveillance Support Center (FSSC), *Relocatable Over The Horizon Radar (ROTHR) Webinar Presented to the Wind Turbine Radar Inteference Mitigation Working Group,* Washington, DC, 2020.

[25] B. Zelenke, *NOAA-IOOS WTRIM Projects Overview,* Washington, DC: National Oceanographic and Atmospheric Administration, 2022.

[26] D. Trockel, I. Rodriguez-Alegre, D. Barrick and C. Whelan, "Impact Assessment and Mitigation of Offshore Wind Turbines on High Frequency Coastal Oceanographic Radar," August 2018. [Online]. Available: https://espis.boem.gov/final%20reports/BOEM_2018-053.pdf. [Accessed 17 September 2023].

[27] NOAA Integrated Ocean Observing System, "OTT: Software Tools for the Mitigation of Wind Turbine Interference in the U.S. IOOS Network," [Online]. Available: https://ioos.noaa.gov/project/ott-hfr-wind-turbine-interference/. [Accessed 18 September 2023].

[28] National Offshore Wind Research and Development Consortium, "Oceanographic HF Radar Data Preservation in Wind Turbine Interference Mitigation," [Online]. Available: https://nationaloffshorewind.org/projects/oceanographic-hf-radar-data-preservation-in-wind-turbine-interference-mitigation/. [Accessed 18 September 2023].

[29] MIT Lincoln Laboratory, "Annual Report," 2021. [Online]. Available: https://www.ll.mit.edu/sites/default/files/page/doc/2022-10/MITLL_2021_Annual_Report.pdf. [Accessed 17 August 2023].

[30] D. C. A. M. a. C. P. E. Kowalski, "Multifunction Phased Array Radar Advanced Technology Demonstrator (MPAR ATD) Nearfield Testing and Fielding," in *IEEE Radar Conference (RadarConf)*, Boston, MA, 2019.

[31] D. A. Crocker, "Wind Turbine Lightning Mitigation System Radar Cross-Section Reduction," Sandia National Laboratories, Albuquerque, 2020.

[32] Booz Allen Hamilton, "Radio-Frequency (RF) Precision Nulling Device," Justia Patents, 11 January 2013. [Online]. Available: https://patents.justia.com/patent/20130222171. [Accessed 17 January 2023].

[33] D. Henley, "84th RADES optimizes nation's LRR systems for air surveillance, national defense," U.S. Air Force, 21 September 2021. [Online]. Available: https://www.af.mil/News/Article-Display/Article/2786101/84th-rades-optimizes-nations-lrr-systems-for-air-surveillance-national-defense/. [Accessed 19 January 2023].

IX. Glossary of Terms

A

ANSR	Airspace Non-cooperative Surveillance Radar
ARSR	Air Route Surveillance Radar
ASR	Airport Surveillance Radar

B

BOEM	Bureau of Ocean Energy Management

C

CARSR	Common Air Route Surveillance Radar
CODAR	Coastal Ocean Dynamics Applications Radar

D

DASR	Digital Airport Surveillance Radar
DHS	U.S. Department of Homeland Security
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy

F

FAA	Federal Aviation Administration
FSSC	Forces Surveillance Support Center

I

IFT&E	Interagency Field Test and Evaluation
IOOS	Integrated Ocean Observing System

M

MIT LL	Massachusetts Institute of Technology’s Lincoln Laboratory
MPAR	Multi-Function Phased Array Radar
MOU	memorandum of understanding

N

NAS	National Airspace System
NEXRAD	Next Generation Weather Radar

R

RAG	Range-Azimuth Gate
ROTHR	Relocatable Over-The-Horizon Radar

S

SDTS	Stationary Doppler Target Suppressor
SENSR	Spectrum Efficient National Surveillance Radar
STARS	Standard Terminal Automation Replacement System

U

USWTDB	U.S. Wind Turbine Database
W	
WTRIM	Wind Turbine Radar Interference Mitigation
Wx	weather

Appendix A. Wind Turbine Radar Interference Mitigation Working Group

The memorandum of understanding establishing the Wind Turbine Radar Interference Mitigation working group was put into effect in March 2015. Signatory members include those agencies listed in Table A-1 with their corresponding departments and websites, with the exception of the U.S. Department of Homeland Security agreeing to participate as an observer. While the Bureau of Ocean Energy Management did not originally sign the memorandum of understanding, they joined as a full member of the Wind Turbine Radar Interference Mitigation working group in 2018.

Table A-1 - Signatory Members of the Wind Turbine Radar Interference Working Group

Agency	**Department**	**Website**
U.S. Department of Energy	Wind Energy Technologies Office	http://www.energy.gov/eere/wind/wind-energy-technologies-office
U.S. Department of Defense	Military Aviation and Installation Assurance Siting Clearinghouse	www.acq.osd.mil/dodsc/
Federal Aviation Administration	Office of NextGen	Next Generation Air Transportation System (NextGen) | Federal Aviation Administration (faa.gov)
National Oceanic and Atmospheric Administration	National Weather Service Radar Operations Center Integrated Ocean Observing System	www.roc.noaa.gov/WSR88D/ https://ioos.noaa.gov/
Bureau of Ocean Energy Management	Office of Renewable Energy Programs	http://www.boem.gov/renewable-energy

Appendix B. Wind Turbine Radar Interference Mitigation Memorandum of Understanding

MEMORANDUM OF UNDERSTANDING
Establishment of the Wind Turbine Radar Interference Mitigation Working Group

Between the Following U.S. Federal Government Agencies

DEPARTMENT OF DEFENSE (DOD)
DEPARTMENT OF ENERGY (DOE)
DEPARTMENT OF HOMELAND SECURITY (DHS)
FEDERAL AVIATION ADMINISTRATION (FAA)
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA)

I. PURPOSE.

A. This Memorandum of Understanding (MOU) establishes a general framework of cooperation and coordination between the forenamed agencies. Its purpose is to mitigate the technical and operational impact of wind turbine projects on critical radar missions. The goals of the Interagency effort include:

   a. Develop near (5 years), Mid (10 Years), Long term (20 years) mitigation solution recommendations. These will be primarily technology driven but will also extend to policy and legislative proposals as necessary
   b. Determine funding requirements to implement workable solutions and include a process for each MOU participant to fund execution of specific near, mid and far term mitigation as outlined in Section II

II. REQUIREMENTS

A. Whereas the DoD, DOE and the DHS have been tasked by internal management and in some cases, additionally by Congress, to identify wind turbine/radar interference mitigation solutions; their representatives will:

   a. Take the lead in the organization of an Interagency team modeled after the former Interagency *Field Test & Evaluation* program
   b. Coordinate the development of agency budgets and the commitment of funding required for studies, field tests or other agreed to expenditures based on the principle of cost-sharing commensurate with meeting agency equity needs

15-5-1452

Figure B-1 – The official memorandum of understanding for the Wind Turbine Radar Interference Mitigation working group