Hindawi
International Journal of Aerospace Engineering
Volume 2022, Article ID 1083717, 9 pages
https://doi.org/10.1155/2022/1083717

Review Article

Mitigation Measures for Windfarm Effects on Radar Systems

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Received 12 December 2021; Accepted 24 March 2022; Published 11 April 2022

Academic Editor: Chen Pengyun

Windfarms can have a significant impact on radar systems, especially air surveillance radar. This is because it is usually designed to show only moving targets and cancel out stationary objects. However, the rotation of wind turbine blades can be detected by radar as a false flight or target. Clutter or interference caused by windfarms can reduce radar sensitivity in critical regions, making real targets disappear. This could in turn affect the deployment of windfarms and lead to the cancellation of future renewable energy projects and plans. This paper presents the different strategies and techniques used to mitigate the windfarm impact on radar systems. Precisely, we aim throughout this article to classify the main currently adopted approaches, view the recent trends and research directions in this field, and try to trace the advantages and drawbacks along with the challenges of deploying such schemes.

1. Introduction

Wind energy is rapidly becoming one of the promising solutions for renewable and clean energy [1]. This energy is harvested by utilizing wind turbines to convert the wind kinetic energy to electrical energy. Wind turbines are usually gathered in massive areas to establish what so called windfarms. These grouped turbines in the same region can significantly affect radars, especially on aviation monitoring radars, as they are normally intended to show just moving targets and cancel out fixed objects. The wind turbine turning blades can be detected by radars as false flights or targets. The clutter or interference created by the windfarms can desensitize the radar in the windfarm region, making real targets vanish. Thus, this can affect the windfarm deployment and may cause cancellation of renewable future projects and plans [2]. There are different solutions to overcome these challenges and mitigate the impact of the windfarm on radar systems. Many of these solutions were developed to create "Windfarm Compliant" radars, which would prevent radars from hindering the development of wind energy [3]. While neither offers total mitigation, there are several alternatives and combinations of options that come close to achieving this goal.

Generally, the impact of windfarms in the radio radar line of sight causes a decrease in target detection capability in the area due to the following problems [4–7]:

(i) *Clutter*. The accumulation of unwanted returns that occurs in the vicinity of the windfarm due to the detection of echoes from wind turbines

(ii) *Desensitization*. A reduction of the desired aerial objects detecting possibility in the space that extends over and around the windfarm at every angle and range

The above two issues cause an overall radar performance degradation within the affected regions which result in loss of wanted target plotting and tracking. This paper gives the reader an overview about the promising approaches and techniques that able to cancel interference caused by windfarms to appropriate degree.

The windfarm effect mitigation measures can follow different strategies which may include combination of schemes and could be broadly categorized as shown in Figure 1. The rest of this paper is aimed at describing those techniques and addressing the advantages and problems of deploying each of them.

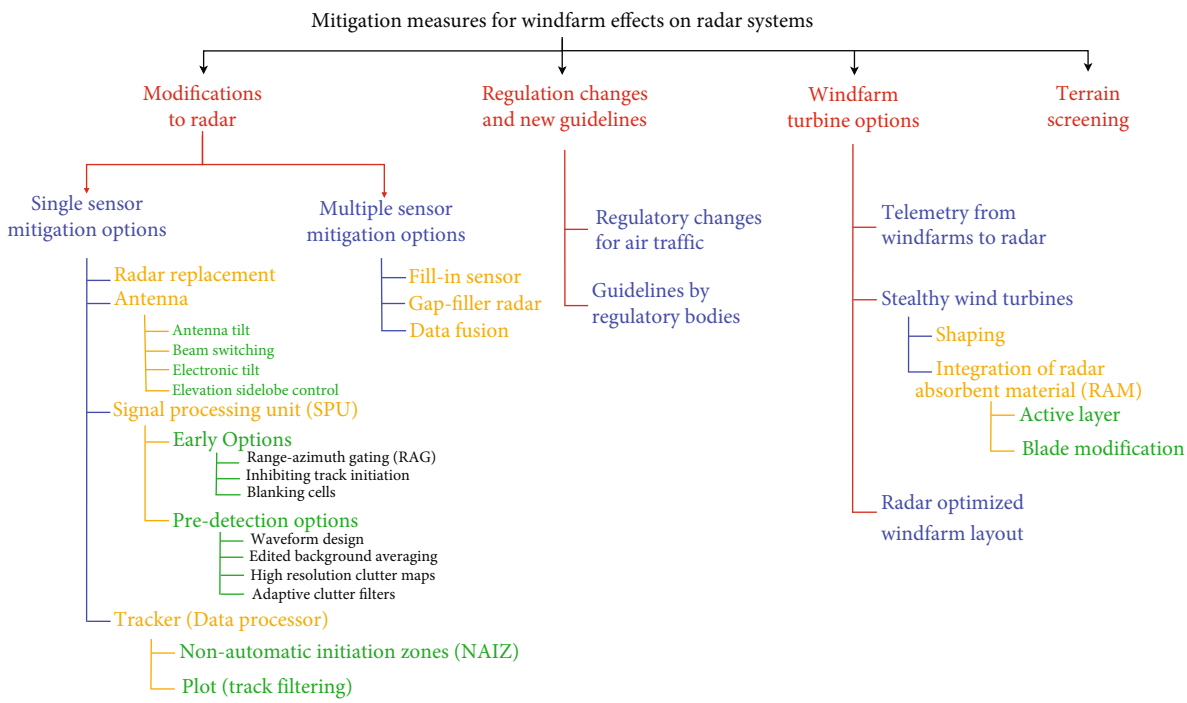

Figure 1: Mitigation measures for windfarm effects on radar systems.

2. Modifications to Radar

This section is dedicated to address the alternatives which can be adopted in the radar system itself to mitigate the windfarm effects. The key choices of this category include as follows.

2.1. Single Sensor Mitigation Options. Sometimes, windfarm lies inside the area covered by the direct line of sight radiation of an operating radar; in this situation, there are variety of choices to mitigate the undesired windfarm impact by at the radar itself involving the following practices.

2.1.1. Radar Replacement. In case when the radar does not have the capabilities to mitigate windfarm interference, then, it is more cost-effective to replace the radar. This replacement can be scheduled during the old system upgrading phase. The upgraded radar systems should integrate multiple-dimensional detection, improved processing unit, and enhanced pulse waveforms to differentiate the real target returns from the undesired wind turbine signature. More specifically, in some scenarios, it is much cost effective to replace the old radar system with an updated one to allow the coexistence with the promising windfarm projects, especially, if we know that the installation cost of one radar is estimated to be between 3 and 8 million USD, compared to the cost of a wind turbine of 2 to 4 million USD to produce about 0.5 million USD of electric energy annually, i.e., (5×10^6 kilowatt hour (kWh), at 10 cents per kWh retail), keeping in mind that windfarm will have tens to hundreds of turbines [8, 9].

2.1.2. Antenna. In this subsection, we address that the windfarm interference mitigate options achieved via applying adjustments to the radar antenna system. They include the following choices.

(1) Antenna Tilt. This mitigation measure is accomplished by changing the radar antenna tilting to cut back or at least reduce the undesired reflection resultant of the illumination of a windfarm.

The main drawback: if the turbine radar cross section (RCS) is larger than a specific value, then, having a large antenna tilting is required and that can intolerably degrade detection performance of the radar for the low altitude targets at long range over the whole azimuth plane of the radar [4].

(2) Beam Switching. In some radar systems such as two-dimensional air traffic control (2D-ATC), it is possible to use two beams and switch between them at a preset range R_s to detect the low elevation targets at long range and high elevation targets at short range. The desensitization at the low altitude of the short range beam can be utilized by increasing the switch-over distance R_s beyond the boarders of the windfarm and consequently lessening its detection probability, while keeping up long distance detection of low altitude aircraft and targets inside the long range beam.

The main drawbacks are as follows:

(i) It might not completely mitigate the effect of the massive RCS turbines because of the desensitization at the short distance beam

(ii) In the large windfarms, the detection likelihood of desired targets will be reduced against the range R_s

(3) Electronic Tilting. Generally, the three-dimensional air-defense (3D-AD) radar utilizing phased arrays are efficient in using electronic tilting (E-tilting) by adjusting the phase and magnitude of the array weighting coefficients. This E-tilting adjustment is often applied to restricted sectors of azimuth plane, so it maintains low level detection performance over the remaining search volume [10].

(4) Elevation Sidelobe Control. A further good advantage of using the adaptive phased arrays in the elevation plane is the resulting capability of controlling the sidelobe, where it is possible to suppress the sidelobe level of the low altitude beams by optimizing the weighting coefficients of phase/amplitude across associate array elements [11].

2.1.3. Signal Processing Unit (SPU). Signal processing mitigation options can be divided into two main categories.

(1) Early Options. These types of signal processing are usually carried out within the postdetection phase (as soon as the radar has detected the existence of the wind turbine). They may involve as follows:

Range-azimuth gating (RAG): simply it means a set up in the radar signal processing unit in the receiver to prevent echoes in determined (range and azimuth) slice which is similar to a pie shape. Then, each slice into range can be electronically filtered out at the radar output [12].

Inhibiting track initiation: it means suppressing tracks of being started in user-defined range/azimuth [13].

Blanking cells: this implies eliminating one or more cells that associate to the significant levels of clutter from the windfarm [14].

The main drawback: these processes are going to create a blind region in the vicinity of the windfarm preventing the detection of desired targets (true aircraft), which, of course, will cause ATC disruption in that area.

(2) Predetection Options. Those processes are implemented to untreated/raw input signal, i.e., prior to the detection of the objects at the radar [12, 15]. These signal processing mitigation options may incorporate the following:

(i) *Waveform design*: because the transmitted pulse width determines the volume of sidelobes, this means that shrinking the duration of transmitted radar pulses can reduce the range of the expected desensitization. Old radar systems which use magnetron transmitters naturally use narrow unmodulated pulses. Therefore, they will not experience range sidelobe impact. On the other hand, modern systems which use solid-state or traveling-wave tube (TWT) transmitters usually adopt a combination of wide modulated pulses to detect the targets at long range and unmodulated or narrow modulated pulses to detect the objects at short ranges. The absence of sidelobes for narrow pulses could be used along with increasing the (short/long) switch over distance to farther than the windfarm area, so that diminish wind turbine impact and keeping it at most limited to spots where they are actually fallen into [16].

The difficulties of this option are as follows:

(a) The limited power short distance ATC systems might be at a disadvantage for the reason that they are incapable to transmit highly enough power to recognize small aircrafts at longer distances using short pulses

(b) This mitigation alternative does not remove wind turbine clutter; however, it does avoid desensitization over wider distances

(ii) *Edited background averaging*: in some cases, random and unusually large returns reflected from windfarm areas can bias the estimate of the background noise average, which may lead to larger threshold level and consequently negative impact on the radar detection performance. However, this burden can be mitigated by omitting those abnormally large values from the noise average calculations. A simple sorting technique along with the statistics of the history of the background noise measurements can be helpful to determine those extremely diverged values [17].

The main drawback: the above scheme dose not mitigate windfarm interference (clutter) on radar system; however, it decreases desensitization over spread out distances. Hence, it is more successful with systems which use narrow pulses than those using wider pulses, because sidelobe interference of the latter one can considerably contribute into the background noise.

(iii) *High resolution clutter maps*: on the other hand, when the system uses large cells of clutter map with an enormous amount of wind turbine reflections occur inside them, the radar detector can be severely desensitized. The preferred alleviation of this impact is to utilize High Resolution Clutter Maps (HRCM), where the clutter cell size is very much diminished, which will eventually limit the area of desensitization spread. Similarly, by allowing separate HRCM in the elevation plane of the multiple beams of the air-defense radars, the extended altitude desensitization could also be prevented. Both of these HRCM mitigation schemes could remove permanent wind turbine clutter and minimize the desensitization impact to the lowest possible level [18].

(iv) *Adaptive clutter filters*: the objective of the implementation of adaptive filtering is to eliminate the

wind turbine clutter effect on radars. This filtering process typically determines the undesired wind turbine signature, then, subtracts it from the input radar signal and interpolates the noncorrupted outcomes to reconstruct the desired signal. This adaptive filtering process utilizes both of the in-phase and the quadrature phase components of the incoming electric field as an input data [12, 19–21].

The difficulties of this option are as follows:

(a) The complication of distinguishing the wind turbine signature as a result of its time varying nature

(b) Usually weather radars do not send I/Q data, instead they transmit information based on that, such as radial velocity and reflectivity. Therefore, the adaptive clutter filter should be implemented in the signal processor of the radar

(c) This filtering must be fast and reliable; therefore, it should be done only for the radar cells which contain wind turbines [12]

The main drawback: all the aforementioned predetection mitigation options involve highly cost radar recertification.

2.1.4. Tracker/Data Processor. There are numerous possible surveillance tracker alternatives to cancel windfarm effects. Since the tracking is done after the detection process in the radar system, therefore, these options are practical to only alleviate the effects of tracking and clutter, but they are not used to mitigate the desensitization.

(1) Nonautomatic Initiation Zones (NAIZ). The initiation of new tracks from the inside of the windfarm can be prevented by disabling the automatic track imitation in the windfarm vicinity, which consequently will reduce the tracking computation complexity [22].

(2) Plot/Track Filtering. The advanced digital tracker (ADT) is an example of the systems used in the radars that are working in the windfarm regions. They are capable to erase of permanent plots resulting from those windfarms, so they do not appear on the radar displayer, and prevent their effect on tracking of moving aircrafts, see Figure 2. Also, these systems use advanced filtering algorithms exploiting the characteristics of the plots and the candidate track to accurately determine them. It is worthy to mention that these kinds of plot/track filtering processes do not enhance on their own the performance of small target detection in the region of windfarm. However, if the signal processing unit detection level is slightly adjusted to let for higher target detection (which of course will increase the rate of false alarm), then, the unreal targets can be deleted by the plot/track filtering, whereas it enhances the plotting and tracking of the detected real targets. Another feature of the choice of the plot/track filtering is that they can be implemented as additive or supplementary options requiring only minor adjustment to be done on the existing radar system [23].

2.2. Multiple Sensor Mitigation Options

2.2.1. Data Fusion. The term "data fusion" can include an extensive variety of complicated technologies, and it is typically referring to exchanging data between separate sensors. This can be established by utilizing the overlapping coverage of multiple radars above a specific region [24]. In this paper, we consider the data exchange between the fill-in sensors or radars and the main radar as depicted in Figure 3. So, as soon as an appropriate fill-in radar position is chosen, it will be an essential task to feed its information and fuse it with the data of the main radar.

In the context of the mitigation of windfarm effects on the radar systems, the data fusion is accomplished in its easiest forms by using a single fill-in radar and updating (replacing) the plot data from the main radar by the plot data from the fill-in radar within the location of the windfarm. This approach is referred to as "Mosaicing." This process is much more complicated and pricey in the multiradar sensor case which of course allows for better mitigation performance.

2.2.2. Fill-In Sensor/Gap-Filler Radar. Similar to what discussed in the previous subsection, to overcome the windfarm interference and clutter which could cause unacceptable loss of radar coverage, it is also crucial to consider deploying supplementary gap-filler radars. This approach of using gap-fillers can be established by utilizing one or multiple sensors or even other existing radars within the main radar observation coverage. Then, the collected information from these sensors is combined via proper data fusion algorithms. This scheme can significantly make the clutter mitigation process easier in the main radar system [9, 26]. The implementation of the gap-filler radars should be planned, so that their positions assure that they will not illuminate the wind turbines. Therefore, they can detect the targets which are hidden in the main radar.

To extend the radar coverage, it is possible to use more than one sensing radar in the blind spots where the main radar detection performance is reduced by the reflected interference and cluster. Accordingly, the plots which come from such sensors can be combined with the main radar plots using advanced plot fusion processes. The extra fused data could be return from an associate existing radar system or from a newly deployed radar. In the case of deploying new radars, they should be cost-effective ones, and they should be specifically designed to increase the target detection likelihood in their small planned regions [12].

The challenge: it is difficult to plan for an optimum location of the fill-in sensor or gap-filler radar.

3. Windfarm/Turbine Options

In this section, we address the mitigation options that can be adopted in the windfarm itself, utilizing the new design and layout (configuration) of wind turbines and the new advancements in the structural and material technologies to reduce the undesired reflected signature towards the radar

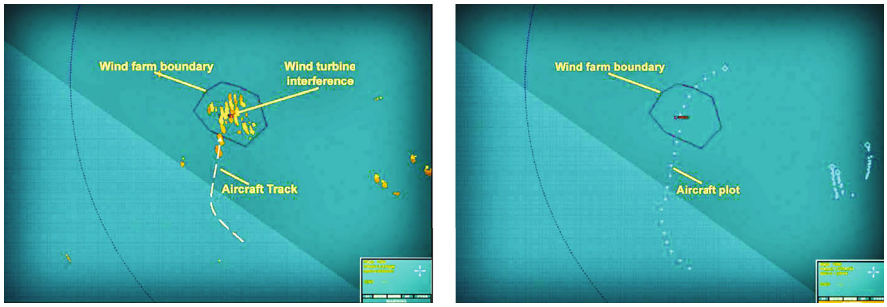

Figure 2: Plot/track filtering.

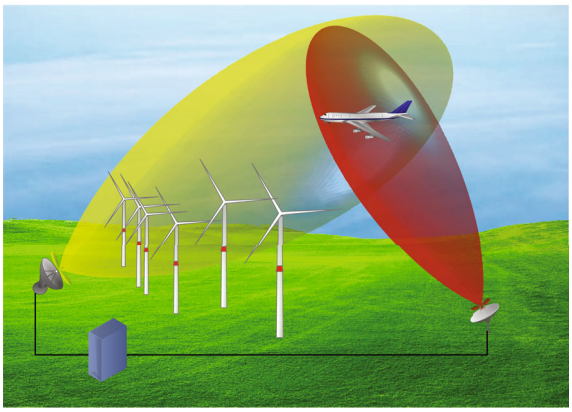

Figure 3: Illustration of data fusion between two radars. The right radar is not affected by wind turbines clutter [25].

system. The classification of the major options of this approach can be organized into as follows.

3.1. Telemetry from Windfarms to Radar. In spite of the fact that it might be feasible to utilize advanced and complex radar information processes to clear out the undesired turbine radio echoes while saving the returns coming from real targets, it is much easier to accomplish the same task if the real configurations of the turbines were known to the radar processor in real time, i.e., at each moment.

Information about the instantaneous conditions of each turbine (phase, precise speed, blade angle, and azimuth direction of the turbine axis) could be transmitted to the radar processor. The information transmission rate is very low, most likely to be less than 100 bps for every turbine, and the turbine-mounted sensors required for the four mentioned values are simple and not costly. Supplied with this data, the processor, with the support of a generally basic model of the turbine radar cross section, could make an accurate computation of the time-varying signal strength anticipated from every turbine and remove it systematically from the radar input signal [9].

Problem: robust networking system is needed; also, substantial information handling and execution difficulties may exist.

3.2. Stealthy Wind Turbines. Another windfarm-based mitigation choice is the treatment of turbine blades to make them stealthy, which in result will reduce the turbine RCS and consequently minimizes the unwanted interference signature produced by the windfarm turbines [12, 27–29].

Constraints are as follows:

(i) The huge wind turbine surface area dictates that the expense for each 1 m^2 of stealth treatment should be as little as possible

(ii) Each and every critical addition in the turbine or its part size is restrictive because of the bearing on the total structure. For instance, the pressure on the gearbox can be seriously increased as a result of the blade coating

(iii) The aerodynamic characteristics which controlled by shape of the turbine blades should be precisely considered

The roughly expected RCS decrease due to applying the stealth coating is near (15-30 dBs); eventing, this is not enough to totally alleviate windfarm impact on the radar system, yet it will substantially enhance the capability of other radar-based mitigation alternatives. Stealth methods are fundamentally based on adjusting the turbine body by reshaping and coating (covering the with radar signal absorbing materials to weaken the reflections to the radar). For instance, one of the options is reshaping the tower into a more funnel body can help in scatter the undesired echo away from the radar. Also, it is possible to coat the nacelle with radar absorbing materials (RAM) or it can be reformed into shape, depending on which is most cost-effective. On the other hand, blade stealth treatment is much more complicated, because of the shape of the blades and their structural composition, where they should be made of different material layers joined to make a light, solid structure and must incorporate some sort of protection against lightning [12]. Generally, the best results of such a promising approach can be obtained by the utilization of the development of the following two options.

3.2.1. Shaping. This approach is based on redesigning the turbine and nacelle frame to maintain the radar signal reflection as low as possible.

(i) A good turbine tower reforming can lead to an enormous decrease in the RCS with an average of 30 dBm^2

(ii) The preferred technique to reduce reflection from the wind turbine towards the radar is reshaping the nacelle. This method can achieve a reduction of about 30 dBm^2 of the turbine signature on the radar system, and that can be accomplished for instance by reforming the nacelle sides into three surfaces and expanding the slant angle [27]

3.2.2. Utilization of Radar Absorbent Material (RAM). Most research work in the field of wind turbine stealth technology has focused on reducing the signature of the turbine's blades on radar system. It is claimed by many research groups that the blades' treatment would change or decrease their radar signature.

(1) Active Layer. In this scheme, the mitigation strategy is based on the idea of laying some sort of active layer on the outer side of the turbine blades to dynamically modulate the blade Doppler signature. These processes could make the Doppler frequency shift of the blades to lie outside the range of operating frequency of the radar [9, 30, 31].

Problem: the abovementioned adjustments to the outer surface of the turbine blades may lead to undesirable disruption to their aerodynamic characteristics and durability.

(2) Blade Modification. A different option proposed by QinetiQ is to modify the contents of the structure of the glass fiber reinforced polymer (GRP), which is the blade made of [32]. This modern industrial innovation will reduce the signature of the turbine blades without compromising their basic quality and structural strength. A reduction of about 15 dBm^2 can be accomplished for the blades utilizing a mix of Salisbury screen [33] and circuit analogue radar absorbent material- (CARAM-) based designs [27]. Boldly speaking, it is stated in [34, 35] that the integration of stealth radar-absorbent material into turbine blades can lessen the impact on radar systems up to 99%.

Problems are as follows:

(i) The abovementioned reduction in the blade's reflection is highly dependent on the radar operating frequency

(ii) Applying various martial and layers to the surface of the turbine blades can deteriorate their aerodynamic characteristics

3.3. Radar Optimized Windfarm Layout. Another way to diminish the undesired effects of wind turbines on the radar system is by exploiting their configuration (spatial distribution) in the windfarm [36]. This definitely should be accomplished without interrupting the activity of the windfarm. As it is preferable to limit the number of resolution cells engaged by wind turbines for a certain radar area and this can be accomplished by as follows:

(i) Eliminating the turbines which lie inside the direct line of sight of the radar propagation

(ii) Increasing the distance between wind turbines so that they are separately distinguishable, thus, enhancing the target detection in the windfarm region

(iii) Rearranging the turbines to be placed at the border/edge of the windfarm in a circular shape making the radar as the center of that circular arc [12]

4. Regulation Changes and New Guidelines

4.1. Regulatory Changes for Air Traffic. One of the considered solutions in this class of the mitigation measures comes through enforcing some changes in the regulations, such as proposing controlled space in the area of the windfarm. Also, it may include the necessity of stating that transponders are required for all aircraft flying in this controlled area [9].

4.2. Guidelines Published by Regulatory Bodies. Some administrative bodies have distributed new rules to approximate a safeguarding zone distance from the windfarms to prevent their undesired effects on radar system. These guidelines attempt to characterize general rules that are easy for nonexperts to understand [12, 37–39].

For instance, the expanded attention to the problems that wind turbines may cause on weather radars led several organizations, such as the Network of European National Meteorological Services (EUMETNET) [40] and the World Meteorological Organization (WMO) [41] to announce new protocols to control the positioning of windfarms in the vicinity of weather radars, depending on safeguarding separation. As an example, in accordance with these rules presented in [42] and [42, 43], it is panned to locate any windfarm closer than 5 km from a weather radar. Also, windfarm planners are advised to propose their projects of windfarms which are located at a distance within 20 km from the any existing radar to evaluate their expected effects.

5. Terrain Screening

Good planning of windfarm location can lead to a way of using the terrain screening or masking, where terrain can serve as a potential barrier against the radio propagation as shown in Figure 4. In other words, terrain masking can be archived by installing wind turbines on the other side of raised landscape to the radar, so they will be obstructed from the radar signals [24, 44]. This assures that the radar signals will not hit up wind turbines with high power intensity and therefore will prevent the degradation of the overall radar detection performance degradation [4, 6].

Problem: wind turbines usually deployed on offshore or at high landscape, where there is insufficient terrain screening, because of that a substantial portion of the wind turbines reflection affects the radar.

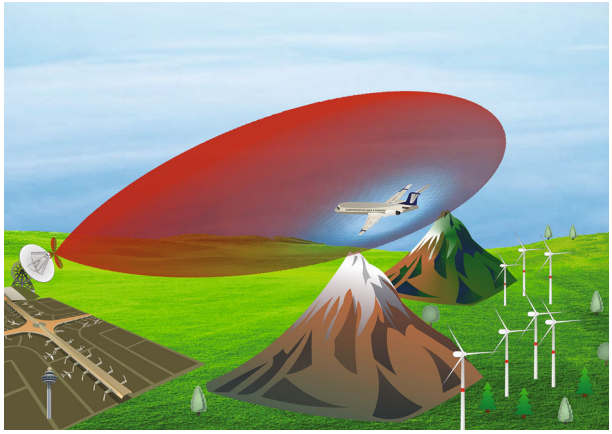

Figure 4: Terrain screening.

6. Recent Development Trends in Radar Clutter Mitigation

In this section, we briefly overview and summarize the development research directions in the field of radar wind-farm clutter mitigation.

For instance, researchers of [45] aimed to enhance the performance of existing radar systems by decreasing wind turbine clutter in radar data. They propose a novel solution based on signal separation approaches to this challenge. That paper displays the radar signal as group sparse in the time-frequency domain. The wind turbine clutter signal, on the other hand, is represented as having a sparse temporal derivative. In order to separate wind turbine clutter and desired radar returns, it formulates the signal separation problem as an optimization problem. Total variation regularization and time-frequency group sparsity are combined in the minimized objective function. The authors also provide a three-window short-time Fourier transform for the time-frequency representation of the radar signal. To illustrate its efficacy, the proposed algorithm was tested on radar systems. The suggested approach considerably enhanced the capacity to recognize wind turbines, resulting in a lower false alarm rate and a more accurate estimation of angular velocity. However, due to the unique needs of radar system applications and data availability, a more thorough examination is still required.

As well, [46] investigates the utilization of the dechirping receiver to reduce interference of a Frequency Modulated Continuous Wave (FMCW) radar system. Following dechirping, the scattered signals from targets generate each, which represent the sum of complex exponentials, whereas the interferences produce chirp-like brief pulses. Using the differing temporal and frequency characteristics of the valuable signals and the interferences, interference mitigation is stated as a challenge of optimization: a sparse and low-rank decomposition of a Hankel matrix generated by lifting the measurement Then, using the Alternating Direction of Multiplier (ADMM) method, an iterative optimization approach is developed to address issue. In comparison to previous approaches, the suggested strategy eliminates the necessity for interference detection while also improving the estimation accuracy of the separated usable signals. A shorter period of signal-to-noise ratio (SNR) for a certain number of received echoes can also result in greater detection accuracy. A longer SNR time gap for each received echo increases the possibility of erroneous detection.

On the other hand, machine learning-based solutions, like as convolutional neural networks (CNNs), offer the potential to drastically lower the costs associated with the traditional strategy of widespread deployment of short-range infill radars. In essence, this new technique would enable faster and more precise target recognition while perhaps reducing false alarms. Costs and mistakes would be drastically reduced as a result. It also does away with the necessity for human interpretation [47].

Although the majority of research publications in this topic focus on marine debris, DNNs have been created to address other forms of clutter as well. Cifola and Harmanny, for example, investigated the problem of clutter/target detection for drone signals contaminated by wind turbine returns in [48]. The performance of a denoising adversarial autoencoder was assessed using the micro-Doppler signatures of drones and wind turbines recorded with X-band continuous wave (CW) radar.

In addition, authors of [49] suggested an artificial intelligence-based categorization method trained on real-world S-band medium-range radar data. After being educated with actual data from an S-band medium-range radar system, it can identify, categorize, and delete unwanted echoes from wind turbines. As an answer to the basic question, are the generated plots created by wind farm turbines, the classification challenge was a binary classification problem. To solve this topic, a hybrid architecture based on convolutional neural networks (CNN) and multilayer perceptrons (MLP) was used. The important principle is to distinguish between two sorts of input vectors: the spectrum, which is an ordered vector with spatial significance, and the second, which contains the features, are spatially irrelevant. After that, the CNN is applied to the spectrum vector, and the MLP is applied to the attribute vector.

Furthermore, [50] develops a machine intelligence approach for identifying micro-Doppler characteristics from an aerial pulsed-Doppler radar sensor. The dynamic nature of windfarm clutters, short-coherent processing interval (CPI) duration, and lack of previous knowledge on the individual wind turbine (WT) in the site are the main hurdles for surveillance mode. Micro-Doppler spectrum segments based on short CPIs serve as the primary feature vectors for detection and classification. To the outputs of aerial plan position indicator scans, both supervised and unstructured techniques, such as artificial neural networks and random forests, are used when machine intelligence algorithm is employed to mitigate the impacts of wind farms on radar systems.

The researchers confirmed that the micro-Doppler spectrum is a suitable aspect when compared to others by modeling a typical aerial multifunction array radar (MFAR) processing operation. Despite the fact that the "training" data is based on electromagnetic models of wind turbines dispersing at various rotation rates, the "testing" data from

real-time radar channels may not be in the same operational states due to differences in orientations and aspect angles.

On the other hand, large-scale simulations based on aerial surveillance scenarios with some measurement data included verified the following benefits for clutter detection algorithms:

(i) The potential of real-time detection with brief and randomly received coherent processing intervals. With additional or longer CPIs, performance improves until the length of received signals fills the complete wind turbine rotation cycle. Furthermore, testing and training pulse bursts come at random for each CPI, with no knowledge of the blade orientation during the CPI. As a result, the target detection method is appropriate for real-world MFAR operations

(ii) The training method does not require any measurable wind turbine clutter truth data or prior understanding of wind turbine dynamics. For training, the wind turbine or target detector merely employs generic, physics-based stochastic simulation data, and prior knowledge of the position, direction, rotation speed, or mechanical condition information is not required

7. Conclusion

In this article, we outlined various procedures and methods to alleviate undesired wind turbines' effects on the radar operation. Specifically, we tried to focus on categorizing the major implemented approaches and view the future research paths in this field. We also attempted to address the potentials and disadvantages as well as the challenge issues of utilizing those techniques.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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