NTIA Technical Report TR-08-454

Assessment of the Effects of Wind Turbines on Air Traffic Control Radars

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ACRONYMS

ATC	air traffic control
ATCBI	air traffic control beacon interrogator
FAA	Federal Aviation Administration
I/N	interference-to-noise ratio
LOS	line-of-sight
MTI	moving target indicator
NF	noise figure
PSR	primary surveillance radar
RCS	radar cross section
SSR	secondary surveillance radar

ASSESSMENT OF THE EFFECTS OF WIND TURBINES ON AIR TRAFFIC CONTROL RADARS

John J. Lemmon, John E. Carroll, Frank H. Sanders, Doris Turner[1]

This technical report describes the results of a study exploring the effects of power-producing wind turbines on Federal Aviation Administration (FAA) air traffic control (ATC) radars. The study was performed to identify the extent to which these effects exist, and to identify mitigation techniques and parameters for such effects. The topics addressed in this report are: review of the current state of the literature on wind turbine effects on ATC radar performance; determination of criteria for recommended no-interference radii between ATC radars and wind turbines; determination of methodology for assessing effects of wind turbines on radars that are within no-interference radii; analysis of the potential for desired targets to be lost in azimuths other than those of wind turbine farms; and consideration of the effects of wind turbines on secondary radar (i.e., ATC beacon interrogator, or ATCBI) performance. The study results indicate that documented cases of deleterious effects from wind turbines do exist and are numerous. Due to the large number of parameters that enter the analysis, a simple, universally applicable set of guidelines for siting of wind turbines near radars is not feasible. However, this study shows that, by making nominal assumptions about turbine characteristics and siting parameters such as local topography, it is possible to develop a universally applicable methodology for assessing potential interference between wind farms and ATC radars.

Key words: air traffic control (ATC) radar; ATC beacon interrogator (ATCBI) performance; wind farm clutter effects; wind turbine clutter effects; wind turbine radar interference effects

1 INTRODUCTION

The advent of large (250-foot-tall and greater) wind turbines for power production (on the order of 1.5 MW) has raised the issue of possible effects on the performance of air traffic control (ATC) radars. Turbines with heights up to 700 feet above ground level have been (or are being) proposed. In particular, the possibility has been raised that wind turbine structures, if positioned with certain geometries and distances relative to ATC radars, might cause those radars to fail to detect desired targets with adverse implications for safety-of-life and national security. Possible mechanisms for target loss might include electromagnetic shadowing, clutter effects, and effects on Doppler (moving target indicator, or MTI, processing) due to turbine blade motion.

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[1] Authors Lemmon, Carroll, and Sanders are with the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U.S. Department of Commerce, Boulder, CO. Author Turner is with the Federal Aviation Administration, Washington, D.C.

The Institute for Telecommunication Sciences (ITS) has been tasked by the Federal Aviation Administration (FAA) to assess the impact of wind turbines on ATC radars. If it is determined that wind turbines pose a threat to the performance of these radars, the FAA has also charged ITS with developing a set of building guidelines to ensure that ATC radars are adequately protected from interference from wind turbines. To this end, a literature search was conducted to determine whether effects on radars from wind turbines have been reported, and, if so, to identify the tools necessary to analyze and assess these effects. The goal of the work is to develop guidelines for safe locations of wind farms in the proximity of ATC radars.

2 REVIEW OF LITERATURE ON WIND TURBINE EFFECTS ON ATC RADARS

Documents [1] and [2] contain no information concerning the actual effects of wind farms on radars. Reports [3], [4], and [5] document numerous cases of the deleterious effects of wind farms on ATC radars observed by British researchers. These reports make it clear that wind farms can indeed pose a threat to radar performance. Similarly, the report [6] by the U.S. Department of Defense contains numerous examples of the effects of wind farms on radars, including ATC radars. Reports [7] and [8] are particularly informative, because they not only document examples of the effects of wind farms on radars, but also provide numerous references to tools necessary to analyze these effects. These references include web sites from which one can download computer codes to model the radar cross sections (RCS) of wind turbines as well as propagation effects and shadowing of radar signals from wind turbines. They also contain tables of simple rules-of-thumb for estimating wind turbine RCSs, assessment methodologies, and recommended mitigation measures. These reports appear to be based on solid physical principles. Chapter 9 of [9] is devoted to modeling and measurements of electromagnetic interference from wind turbines, but is concerned with interference to television signals (as opposed to radar) and was not particularly useful for this study.

From reports [6], [7], and [8], it appears that although researchers in both the U.S. and U.K. have identified interference to ATC radars from wind farms, U.K. researchers have investigated these effects more comprehensively than U.S. researchers. Moreover, the reports are not consistent in their assessment of the effects of wind farms on radars. For example, it is stated in [6] that "as the U.K. flight trials demonstrate, the presence of a wind farm does not appear to significantly affect the performance of SSR (secondary surveillance radar) systems...the U.K. flight trials relied on SSR returns to document actual aircraft positions during the tests." On the other hand, [7] states unequivocally that wind farms can affect the performance of SSR systems and that, "Ghost targets are the most common and noticeable effect on SSR systems." The report also discusses various causes and mitigation measures.

In conclusion, these reports make it clear that the necessary tools for analyzing and assessing the impact of wind turbines on ATC radars exist and are available. They are also clear that the precise impact on radar performance can only be determined on a case-by-case basis. This is because of the many parameters that enter the analysis, including the size and structure of the wind turbines, blade rotation rates, pitch and yaw of the blades, the radar absorbing properties of different materials used in wind turbine construction, the number of wind turbines in a farm, and the spacing of wind turbines, all of which affect the wind farm RCS. In addition, local terrain, radar antenna patterns, and sensitivity thresholds vary on a case-by-case basis. Thus, it is not possible to develop universal guidelines that can be applicable in all scenarios for prescribing a minimum separation between wind farms and ATC radars. However, it is possible to establish conservative estimates on minimum separation between wind farms and ATC radars based on nominal assumptions about the wind turbine RCS, radar transmit power and sensitivity to interference, and propagation conditions.

Taking into consideration the information derived from the literature review, this study begins by determining the line-of-sight (LOS) distance between a proposed wind farm and the radar. The LOS distance is the most conservative estimate of the minimum separation necessary between the wind farm and radar, where radar performance degradation is not expected under ordinary circumstances. Additionally, this LOS conservative estimate can be further reduced by taking into account other mitigating factors such as terrain shadowing, blockages, the impact of radar processing algorithms, and the strength of wind turbine clutter returns. Recommended procedures for dealing with these various factors are discussed in this report.

3 PROCESS FOR ANALYZING WIND TURBINE AND RADAR ELECTROMAGNETIC COMPATIBILITY

The flow chart of Figure 1 outlines the recommended process for determining if a radar may be affected by a nearby wind farm. The process consists of a series of decision-point checks:

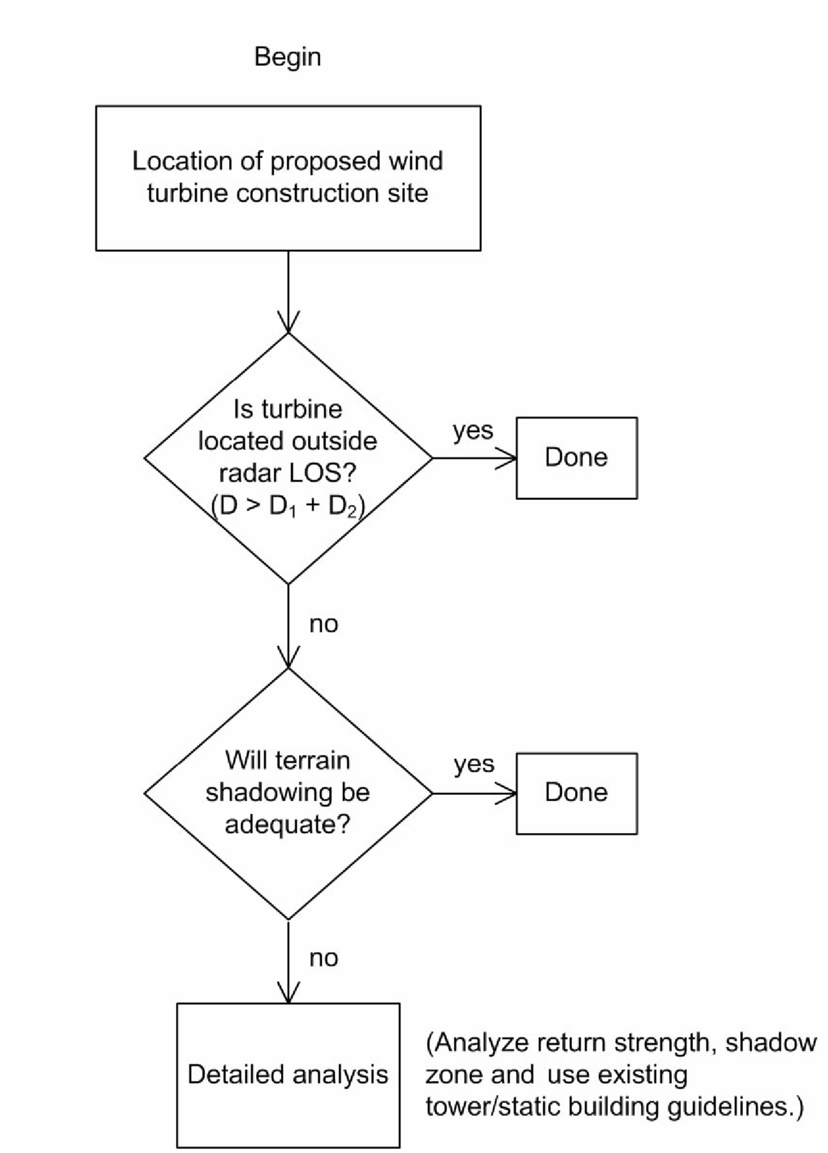

Figure 1. Flow chart to determine if a radar will be affected by a nearby wind farm.

3.1 Line-of-Sight Distance between Wind Turbines and Radar

Due to the numerous different constructions, materials, and individual site circumstances, it is not possible to determine a universally accurate minimum distance where interactions between a turbine and a radar would occur. It is, however, possible to determine a minimum distance where effects from wind turbines would not be anticipated.

The first check proposed (Figure 1) is to examine the distance between the wind turbine location and the potentially affected radar. If the distance is greater than the LOS distance, one would not anticipate any effects from the physical structure or from Doppler-shifted radar returns from the spinning turbine blades.

Below is a schematic illustration of the geometry between a wind farm and an ATC radar at the outer-most edge of the LOS.

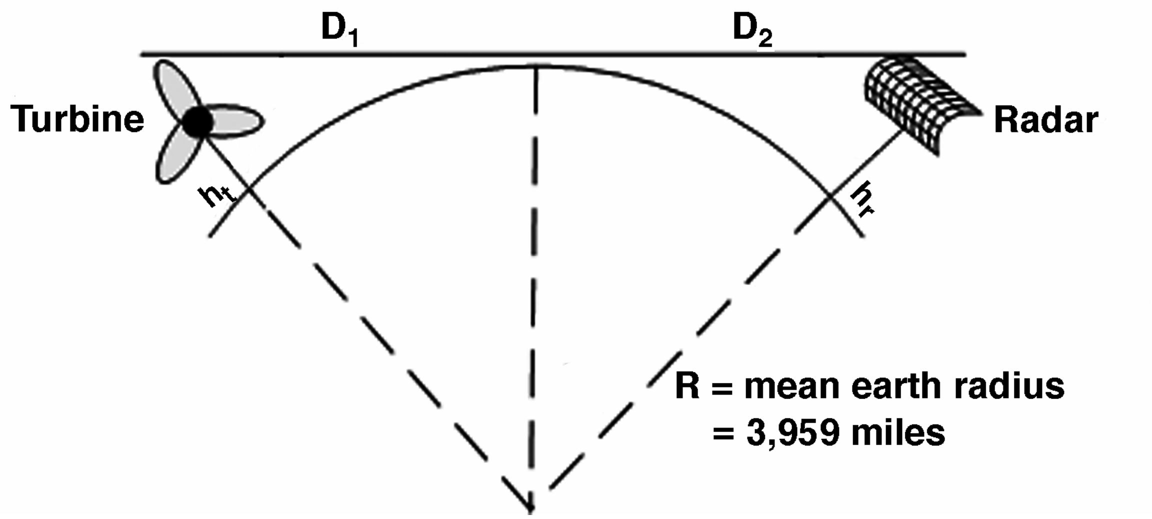

Figure 2. Schematic geometry between a wind farm and a radar at the edge of the LOS.

Using the Pythagorean Theorem,

$$D_i = \sqrt{\left(R + h_i\right)^2 - R^2} \approx \sqrt{2Rh_i} \qquad (1)$$

for $h_i << R$, where:

D_i is the distance of the object from the local horizon of a smooth, round earth;
R is the mean radius of the earth (6380 km = 3959 miles);
h_i is the height of the object above mean sea level.

The refractivity of the atmosphere causes bending of radio waves. This effect can be taken into account by replacing the true earth radius by an effective earth radius. Atmospheric refraction varies widely, depending on the local climate. However, an effective earth radius of 4/3 times the true earth radius is representative of the effect of atmospheric refraction under normal conditions.

Using the 4/3 earth model for atmospheric refraction and equation (1):

$$R \rightarrow \frac{4}{3}R$$

$$D_i = \sqrt{2 \cdot \frac{4}{3} R \cdot h_i} = \sqrt{\frac{8}{3}(3959) h_i}$$

$$D_i = 1.41\sqrt{h_{i\,(\mathrm{ft})}} \text{ miles}. \tag{2}$$

The total LOS between the turbine and radar is then

$$D = D_1 + D_2 = 1.41\left(\sqrt{h_{t\,(\mathrm{ft})}} + \sqrt{h_{r\,(\mathrm{ft})}}\right) \text{ miles}. \tag{3}$$

For example, the height of the radar above mean sea level is 50 feet and the height of the wind turbine is 300 feet. Therefore, the total LOS distance between the two is (using equation (3)):

$$D = 1.41\left(\sqrt{50} + \sqrt{300}\right) = 34.4 \text{ miles}.$$

In other words, if the proposed wind turbine farm is greater than 34.4 miles from the radar, no adverse effects on the radar would be anticipated.

In summary, we present here a methodology that can be used to determine whether a proposed wind farm will present the potential for degradation of radar system performance due to insufficient spatial separation between the farm and a radar station. The most conservative criterion that can be used is one in which the wind farm is located at a separation distance that exceeds 4/3 smooth, round earth, with no terrain effects considered.

3.2 Terrain Shadowing

The first LOS distance check (Section 3.1) assumes a smooth, round earth without the inclusion of terrain considerations. The second proposed check is to examine the terrain surrounding the radar for potential shadowing effects mitigating any effect of the turbines on the radar. If it is determined (e.g., by using a terrain database) that the local terrain will shadow the turbines from the radar, no adverse effects on the radar are expected. It should be pointed out that due to diffraction of radio waves around the terrain blockage, the effective height of the blockage is reduced from the actual height by the radius R_F of the first Fresnel zone, which is

$$R_F = \sqrt{D\lambda}, \tag{4}$$

where λ is the wavelength of the radio waves, $1/D = 1/d_1 + 1/d_2$, d_1 is the distance from the radar to the blockage, and d_2 is the distance from the blockage to the turbine.

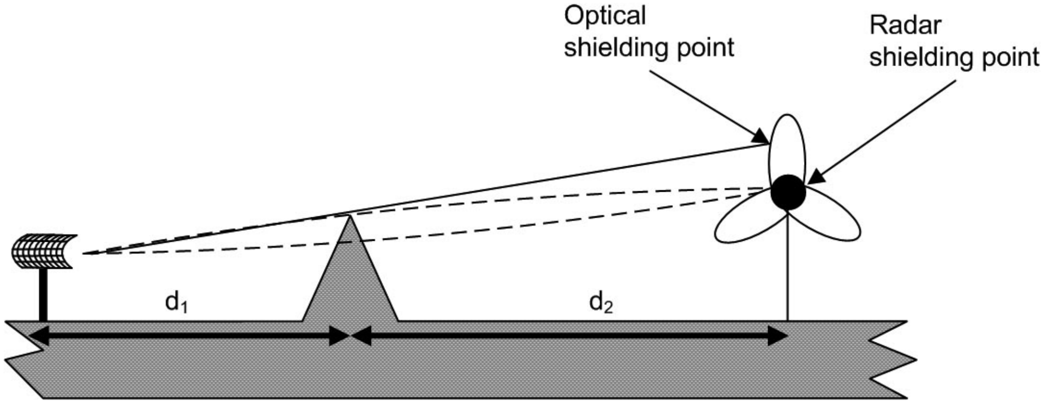

Figure 3. Illustration of first Fresnel zone blockage.

Consider the situation illustrated in Figure 3. The solid line shows the optical shielding point. This is the blocking of the turbine that would be apparent by eye (no significant diffraction). At radar frequencies, however, the dotted lines show the shielding point based on total obstruction of the first Fresnel zone. This radar shielding point can be calculated by subtracting the radius R_F of the Fresnel zone from the height of the obscuring object, and then calculating the optical shielding point using this reduced height for the obscuring object [7].

3.3 Methodology for Assessing the Effects of Wind Turbine Clutter Returns on Radar Performance

If a radar station falls within the 4/3 smooth-round-earth or non-terrain-shadowed radii described in Sections 3.1 and 3.2, then it is possible that scattered energy from the wind farm could adversely affect the performance of the radar receiver by increasing its effective noise floor level. The occurrence of such increased noise could cause desired targets to be lost [11], or could possibly even cause false targets to be generated. The criteria that can be used to assess a threshold for this effect are given in [11]. These are: a power level of scattered energy that is less than -9 dB relative to the radar's noise floor (an interference-to-noise, or *I/N*, level that is equal to or less than -9 dB—see equation (7) below) will not cause adverse effects, and an *I/N* level that is less than or equal to -6 dB will cause few effects. Levels higher than -6 dB may cause measurable losses in desired targets and could cause the generation of some false targets. The following equations can be used to assess whether a wind farm will be expected to exceed these -9 dB (ultra-conservative) and -6 dB (conservative) thresholds.

The strength of the clutter returns is given by:

$$P_{rx} = \frac{P_{tx} \cdot g_{tx} \cdot g_{rx} \cdot \sigma \cdot \frac{\lambda^2}{4\pi}}{\left(4\pi d^2\right)^2},$$

which simplifies to

$$P_{rx} = \frac{P_{tx} \cdot g_{tx} \cdot g_{rx} \cdot \sigma \cdot \lambda^2}{64\pi^3 d^4}, \tag{5}$$

where:

P_{rx} is the received power in watts;
P_{tx} is the transmitted power in watts;[2]
g_{tx} is the transmitter antenna gain in dBi;[3]
g_{rx} is the receiver antenna gain in dBi;
σ is the radar cross section (RCS) of the turbine in square meters;
λ is the wavelength of the operating frequency in meters;
d is the distance between the radar and the turbine in meters.

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[2] For radars using pulse compression, such as the ARSR-4 or ASR-11, the equation input for P_{tx} should be the radar's actual P_{tx} multiplied by the pulse compression ratio. For example, if the uncompressed pulse width is 100 µs, the compressed pulse width is 1 µs, and the actual peak transmitter power is 10 kW, then the value used for P_{tx} in the equation should be [(10 kW)*(100 µs /1 µs)] = 1000 kW = 1 MW.

[3] For ATC radars, $g_{tx} = g_{rx}$. If a turbine is in the near-field of a radar antenna, the turbine effectively acts as part of the antenna, which could possibly alter the antenna's radiation pattern and hence the gain. However, this is only of academic interest because this would require siting of the turbine within tens of meters of the radar antenna, and it is also ruled out by the other criteria discussed in this report.

The calculation of the radar receiver's sensitivity is given by:

$$\text{noise floor(dBm)} = -174 + 10 \cdot \log\left(B_{radar}\right) + NF\ , \tag{6}$$

where:

B_{radar} is the IF bandwidth of the radar in Hz;
NF is the noise figure in dB.

As documented in [11], the highest *I/N* ratio permissible before radar performance degradation occurs is -9 dB. An *I/*N higher than -9 dB may begin to adversely affect radar performance and cause loss of desired targets.

$$\mathrm{P}_{\text{thresh}} = \text{noise floor (dBm)} - 9 \tag{7}$$

For example, if the IF bandwidth of a given radar is 1 MHz and the noise figure (NF) is 5 dB, then the noise floor is (using equation (6)):

$$\text{noise floor (dBm)} = -174 + 60 + 5 = -109 \text{ dBm}\,.$$

The level ($\mathrm{P}_{\text{thresh}}$) at which loss of targets will begin to occur is (using equation (7)):

$$\mathrm{P}_{\text{thresh}} = -109 - 9 = -118 \text{ dBm} = -148 \text{ dBW}\,.$$

For example, what would be the distance (d) at which energy above the -9 dB *I/N* threshold could enter the radar receiver via a sidelobe at 0 dBi gain for a radar with a transmit power of 1 MW and operating at 2.7 GHz? To solve this, the calculation below is performed in MKS units using equation (5). (With respect to the appropriate value of the parameter σ, wind turbine cross sections are discussed in [7] and [12].)

$P_{tx} = 1 \text{ MW} = 10^6 \text{ W}$

Set $\mathrm{P}_{thresh} = P_{rx} = -148 \text{ dBW} = 1.6 \times 10^{-15} \text{ W}$

$g_{tx} = g_{rx} = 0 \text{ dBi} = 1$

$$\lambda = \frac{c}{f_{radar}} = \frac{3 \times 10^8 \text{m/s}}{2.7 \times 10^9 /\text{s}} = 1.1 \times 10^{-1} \text{ m}$$

For a typical wind turbine, $\sigma = 30 \text{ dBsm} = 10^3 \text{ m}^2$

$$
\begin{aligned}
d &= \sqrt[4]{\frac{P_{tx}\cdot g_{tx}\cdot g_{rx}\cdot\sigma\cdot\lambda^{2}}{64\pi^{3}\cdot P_{rx}}} = \sqrt[4]{\frac{10^{6}\cdot 1\cdot 1\cdot 10^{3}\cdot 1.2\times10^{-2}}{2.0\times10^{3}\cdot 1.6\times10^{-15}}}\ \text{m} \\
&= \sqrt[4]{\frac{1.2\times10^{7}}{3.2\times10^{-12}}}\ \text{m} = \sqrt[4]{37.5\times10^{17}}\ \text{m} = 4.4\times10^{4}\ \text{m} \\
&= 44.0\ \text{km} = 27.3\ \text{mi}
\end{aligned}
$$

It might be argued that the radar's MTI processing will remove the display of effects due to scattered energy from a wind turbine farm. But here we are not considering the problem of displaying false targets generated by scattered energy from a turbine farm. Rather, we are considering the problem that energy scattered from a turbine farm will increase the effective noise floor of the radar receiver and hence cause desired targets to be lost. This effect cannot be mitigated by MTI processing.

Although the MTI processing will not eliminate effects that raise the noise floor of the radar, it will mitigate the display of false targets generated by scattered energy from a wind farm. However, it is possible that the radar's MTI threshold will be exceeded by the Doppler shift from the spinning turbine blades. This will be the case if the maximum expected speed of the turbine blade tips exceeds the threshold speed of the MTI processing. Since the maximum blade tip speeds of 1-MW scale turbines are approximately 100 to 200 mph [10], this could occur in situations in which desired target speeds are on the order of or less than 200 mph. If such an MTI-exceedance occurrence is possible for the tip speeds of a proposed wind turbine farm, and the farm does not fall outside the LOS of the radar station, the display of false targets may not be eliminated by the MTI processing.

Nevertheless, the scattered energy that exceeds the MTI threshold is only a fraction of the total scattered energy (most of the energy is scattered from the stationary parts of the turbine and its supporting structure). If this fraction of the energy exceeds the radar noise floor and generates a false target, the total scattered energy is well above the -6 dB (or -9 dB) *I/N* thresholds discussed above. Thus, the criterion that no false targets be generated is much weaker than the criterion for no lost targets and will automatically be satisfied by the requirement for no lost targets. That is, if a wind turbine is close enough to a radar to produce a false target above the MTI threshold, then it is already close enough to exceed the radar's *I/N* threshold for target loss, and hence is close enough to have caused the radar to have lost targets.

3.4 Effects of Shadowing on Detection of Desired Targets

When a radar beam is pointing in the direction of a wind turbine, the resulting blockage of the radar signal creates a shadow behind the turbine. The possibility therefore exists that desired targets in the shadow zone could be lost due to the reduction in field strength of the radar signal. Simulations of wind turbine shadows indicate that the general shape of the shadow is a three-dimensional wedge whose angular extent is of the order 2 degrees or less. The impact on the one-way transmission of field strength from a transmitter to a point p in the shadow depends on the distances between the transmitter, the turbine, and the point p, and can be shown to be [7]

$$\text{Relative field strength inside shadow zone } = 1 - \sqrt{\frac{D_{tp}S^2}{D_{tw}D_{wp}\lambda}}\,, \qquad (8)$$

where:

D_{tp} is the distance from the transmitter to a point, p;
D_{tw} is the distance from the transmitter to the wind turbine;
D_{wp} is the distance from the wind turbine to a point p;
S is the typical width of the wind turbine.

The possibility of lost targets exists if this reduction in field strength reduces the strength of a radar return to a level below the noise floor (or sensitivity) of the radar. This can be assessed by using the methodology of the previous subsection, taking this reduction in field strength into account.

For a primary radar, the effect of shadowing needs to be taken into account for the two-way transmission of the radar signal (thus resulting in a square of equation (8)). Thus, for a target at the point *p*, the decibel reduction in the power of the radar return is:

$$\text{Reduction in Power (dB)} = 40\log\left(1 - \sqrt{\frac{D_{tp}S^2}{D_{tw}D_{wp}\lambda}}\right). \qquad (9)$$

For example (using equation (9)), an ATC radar operating at 2.8 GHz is located 5 kilometers from a wind turbine with a typical (tower) width of 3 meters. A target is located 15 kilometers from the turbine and is in the shadow zone behind the turbine.

$$\lambda = \frac{c}{f_{radar}} = \frac{3\times10^8 \text{ m/s}}{2.8\times10^9 \text{ /s}} = 1.07\times10^{-1} m$$

$$D_{tw} = 5\times10^3 \text{ m}$$

$$D_{wp} = 1.5\times10^4 \text{ m}$$

$$\mathrm{D}_{tp} = D_{wt} + D_{wp} = 2.0\times10^4 \text{ m}$$

$$\begin{aligned}\text{Power reduction of radar return} &= 40\log\left(1 - \sqrt{\frac{2.0\times10^4\cdot9}{5\times10^3\cdot1.5\times10^4\cdot1.07\times10^{-1}}}\right) \text{ dB}\\ &= 40\log\left(1-\sqrt{2.24\times10^{-2}}\right) \text{ dB}\end{aligned}$$

$$\text{Power reduction of radar return} = -2.8 \text{ dB}$$

3.5 Consideration of Wind Turbine Aggregate Effects

Although existing tools enable one to analyze the impact of a single wind turbine on radar performance, less is known about the collective effects of multiple turbines in a wind farm. ATC radar coverage is normally segmented into spatial cells called “resolution cells”. Each cell represents a discrete target processing opportunity. If only a single wind turbine is located in a radar resolution cell, then the forgoing analysis remains valid.

If, however, the spacing and geometry of the turbines are such that there is more than one turbine in each of a radar’s resolution cells, one cannot presumably treat the impact of the turbines on an individual basis. For denser turbine-to-turbine spacings, the combined effects of multiple turbines on RCS and shadowing need to be taken into account. As a first approximation, the effects from individual turbines could be combined in a linear fashion. However, interactions among the turbines could complicate the situation, and this is an area worthy of further investigation.

4 POTENTIAL FOR DESIRED TARGETS TO BE LOST IN AZIMUTHS OTHER THAN THOSE OF WIND TURBINE FARMS

If one or more wind turbines do not cause degradation of radar performance due to interaction with the radar antenna's main beam, then no degradation should result from interactions between the same wind turbines and any of the radar antenna sidelobes. If, however, wind turbines should happen to be positioned in such a way that the interaction with the radar main beam does cause degradation to the radar performance, then radar energy transmitted in its sidelobes will also be reflected from the wind turbines and returned as echoes into those same sidelobes. This transmitted and reflected energy in the sidelobes would constitute clutter returns. If the turbines did not have moving parts, the effect of such returns would be equivalent to any other sort of static clutter. This is not an effect that can be suppressed by MTI processing, inasmuch as the issue here is whether the clutter-return energy raises the noise floor of the radar receiver and hence causes some desired targets to be lost. Since the radar main beam is directed on an azimuth that is, by definition, not that of the wind turbine farm when the effect would occur in the antenna sidelobes, this clutter effect could in principle cause targets to be lost in directions other than that of the wind farm itself. The problem considered in this section is, in the event that radar performance might be degraded when the main beam is directed toward a wind turbine farm (acknowledged to in itself be an undesirable situation), to what extent might desired targets also be lost on azimuths other than that of the wind turbine farm, due to sidelobe interactions with the turbines?

The problem of target loss due to increases in radar receiver noise floor has already been studied and analyzed in detail in an existing NTIA Technical Report [11]. The threshold criterion for no target losses is an I/N level of -9 dB or lower. Thus, the problem that we are addressing here reduces to the issue of determining whether sidelobe clutter from wind turbine structures will cause coupling at an I/N level that exceeds -9 dB.

The methodology for analyzing the I/N level scattered from a wind turbine farm is given in Section 3.4. This methodology is applicable for analysis of this problem as well. If the analysis shows that there is not enough scattered energy from the radar main beam to cause an I/N increase of -9 dB or more when the beam is directed toward the wind farm, then the radar sidelobe scattering will presumably not present a problem either. If, on the other hand, an analysis of the main beam scattering using the methodology of Section 3.4 shows that such scattering can cause an I/N exceedance of more than -9 dB, then additional analysis should be performed to determine whether such exceedance will also occur in the radar's sidelobes. If such exceedance is found to be present for the sidelobes as well as the main beam, then the proposed wind turbine farm will potentially cause target losses to occur in directions other than that of the main beam. Those additional lost-azimuth returns could occur in directions that are even more critical than that of the wind turbine farm itself.

5 CONSIDERATION OF THE EFFECTS OF WIND TURBINES ON SECONDARY RADAR (ATCBI) PERFORMANCE

As mentioned in Section 2, there are conflicting reports in the literature regarding the effects of wind turbines on SSR performance. Whereas it is stated in [6] that SSR performance does not appear to be affected, [7] states that impacts have been reported. It appears that although impairments of SSR performance can occur, they are much less likely than the impacts on primary surveillance radar, or PSR, performance.

Impacts due to shadowing and signal corruption have not been reported. Possible impacts that need to be considered include: errors in bearing and target splits and jumps, collectively referred to here as ghost targets. Errors in bearing have been reported, but are generally less than 2 degrees. Ghost targets caused by multipath from the turbine on the SSR uplink are the most common impairment. This possibility can be assessed by using the methodology in Section 3.4 to calculate the strength of the “false interrogation” reflected from the turbine, and comparing this to the sensitivity of the transponder on the target. Report [7] also presents calculated SSR no-build radii rule-of-thumb values. These values are based on the same methodology as described in Section 3.4 to calculate the strength of the “false interrogation” reflected from the turbine and targets. RCS and transmitter powers also play a role in calculating the no-build radii rule-of-thumb values.

Fundamentally, the effects of wind turbine farms on SSR performance would not be expected to differ from those of static structures, given that SSRs do not employ any processing technique analogous to MTI; in other words, the movement of wind turbine blades should not affect SSR performance per se. The FAA can presumably treat wind turbine farms in the same manner as it treats static structures concerning SSR effects.

6 SUMMARY AND CONCLUSIONS

This technical memorandum describes the results of a study exploring the effects of power-producing wind turbines on FAA ATC radars. The study was performed to identify the extent to which these effects exist, and to identify mitigation techniques and parameters for such effects. The topics that are addressed in this report are: review of the current state of the literature concerning wind turbine effects on ATC radar performance; determination of criteria for recommended no-interference radii between ATC radars and wind turbines; determination of methodology for assessing effects of wind turbines on radars that are within no-interference radii; analysis of the potential for desired targets to be lost in azimuths other than those of wind turbine farms; and consideration of the effects of wind turbines on secondary radar (ATCBI) performance. The study results indicate that documented cases of deleterious effects from wind turbines do exist and are numerous. Due to the large number of parameters that enter the analysis, a simple, universally applicable set of guidelines for siting of wind turbines near radars is not feasible. However, this study shows that by making nominal assumptions about turbine characteristics and siting parameters such as local topography, it is possible to develop a universally applicable methodology for assessing potential interference between wind farms and ATC radars.

Regarding the state of existing literature, studies by both British researchers and the U.S. Department of Defense have concluded that wind farms can indeed pose a threat to radar performance. The studies have gone beyond theoretical considerations—both groups have documented numerous instances of adverse performance effects of wind farms on radars, including ATC radars. Necessary tools for analyzing and assessing the impact of wind turbines on ATC radars are available, see [7] and [8]. These techniques have been summarized in this report.

Although existing tools enable one to analyze the impact of a single wind turbine on radar performance, less is known about the collective effects of multiple turbines in a wind farm. If the spacing and geometry of the turbines are such that there is no more than one turbine in each of a radar’s resolution cells, one can presumably treat the impact of the turbines on an individual basis. For denser turbine-to-turbine spacings, however, the combined effects of multiple turbines on RCS and shadowing need to be taken into account. As a first approximation, the effects from individual turbines could be combined in a linear fashion. However, interactions among the turbines could complicate the situation, and this is an area worthy of further investigation.

Given that wind farms can cause degradation in the performance of nearby radar stations, we have developed in this report a methodology for analyzing the potential impact of proposed wind turbine farms on existing radar stations. The flow of this methodology is given in Figure 1. This methodology is as follows.

The first step is the determination of whether the farm falls outside an absolute no-interference radius. The methodology presented in Section 3.1 can be used to determine whether a proposed wind farm will present the potential for degradation of radar system performance due to insufficient spatial separation between the farm and a radar station. This is the most conservative criterion that can be used, in which the wind farm is located at a separation distance that exceeds

4/3 smooth, round earth, with no terrain effects considered. This is the approach that can be used to determine absolute, no-interference radii between radars and wind farms.

For radars that fall within the no-interference radius that is determined from the 4/3 smooth-round-earth analysis of Section 3.1, supplemental analysis needs to be performed in which the effects of terrain are taken into account. The proposed check is to examine the terrain surrounding the radar for potential shadowing effects mitigating any effect of the turbines on the radar. If it is determined (e.g., by using a terrain database) that the local terrain will shadow a wind farm from the radar, no adverse effects on the radar are expected. It should be pointed out that due to diffraction of radio waves around terrain blockage, the effective height of the blockage is reduced from the actual height by the radius R_F of the first Fresnel zone, as described in Section 3.2.

If a radar station falls within the 4/3 smooth-round-earth or non-terrain-shadowed radii described in Sections 3.1 and 3.2, then it is possible that scattered energy from the wind farm could adversely affect the performance of the radar receiver by increasing its effective noise floor level. The occurrence of such increased noise could cause desired targets to be lost [11], or could possibly even cause false targets to be generated. The criteria that can be used to assess a threshold for this effect are given in [11]. An *I/N* level of less than -9 dB will not cause adverse effects; an *I/N* level that is less than or equal to -6 dB will cause few effects. *I/N* levels higher than -6 dB may, however, begin to cause measurable losses in desired targets and could cause the generation of some false targets. Equations that can be used to assess whether a wind farm will be expected to exceed these -9 dB (ultra-conservative) and -6 dB (conservative) thresholds are provided in Section 3.3. A methodology is also provided in Section 3.4 for the determination of whether a wind farm can potentially cause the loss of desired targets due to shadowing effects.

Radar energy transmitted from a sidelobe could be reflected from a wind turbine back into the sidelobe and cause a loss of desired targets on an azimuth other than that of the wind farm. This issue is considered in Section 4. The mechanism of target loss would be an increase in the radar receiver's noise floor due to the sidelobe energy. If an analysis of the main-beam scattering using the methodology of Section 3.4 shows that such scattering can cause an I/N exceedance of more than −9 dB, then additional analysis should be performed to determine whether such exceedance will also occur in the radar's sidelobes. If such exceedance is found to be present for the sidelobes as well as the main beam, then the proposed wind turbine farm will potentially cause target losses to occur in directions other than that of the main beam, and additional lost-azimuth returns could occur in directions that are even more critical than that of the wind turbine farm itself.

Finally, the potential effects of a wind farm on a radar station's SSR functionality is considered in Section 5. These effects are not expected to differ from those of static structures on SSR performance. The FAA can presumably treat wind turbine farms in the same manner as it treats static structures concerning SSR effects.

In conclusion, there is no universally applicable methodology or criterion to establish the total lack of adverse effects from a wind turbine farm on a radar station, other than to restrict wind farm locations to radii that exceed LOS (including 4/3 smooth-round-earth refraction effects). If closer radii are to be considered as possibilities, then the methodologies and analysis approaches provided in this report need to be used on a case-by-case basis to assess potential impacts. Such analyses will need to take into account the specific operating characteristics of proposed wind turbine farms, such as detailed information about design, materials, and expected blade movement characteristics (e.g., pitch angles and rotational speeds).

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15. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This technical report describes the results of a study exploring the effects of power-producing wind turbines on Federal Aviation Administration (FAA) air traffic control (ATC) radars. The study was performed to identify the extent to which these effects exist, and to identify mitigation techniques and parameters for such effects. The topics addressed in this report are: review of the current state of the literature on wind turbine effects on ATC radar performance; determination of criteria for recommended no-interference radii between ATC radars and wind turbines; determination of methodology for assessing effects of wind turbines on radars that are within no-interference radii; analysis of the potential for desired targets to be lost in azimuths other than those of wind turbine farms; and consideration of the effects of wind turbines on secondary radar (i.e., ATC beacon interrogator, or ATCBI) performance. The study results indicate that documented cases of deleterious effects from wind turbines do exist and are numerous. Due to the large number of parameters that enter the analysis, a simple, universally applicable set of guidelines for siting of wind turbines near radars is not feasible. However, this study shows that, by making nominal assumptions about turbine characteristics and siting parameters such as local topography, it is possible to develop a universally applicable methodology for assessing potential interference between wind farms and ATC radars.

16. Key Words (Alphabetical order, separated by semicolons)

air traffic control (ATC) radar; ATC beacon interrogator (ATCBI) performance; wind farm clutter effects; wind turbine clutter effects; wind turbine radar interference effects

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