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Effects of Wind Turbines on High Frequency Surface Wave Radar

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Abstract

A study is carried out on the effects of a wind turbine on a potential High Frequency Surface Wave Radar system at Hartlen Point, Nova Scotia. The scope of the study is limited to the model V-47 wind turbine produced by Vestas Wind Systems. The study considers two effects of the turbine on the radar. The first effect is the production of Radio Frequency Interference (RFI) by the turbine. Measurements of an existing wind turbine determine an upper bound on the contribution of the turbine to the local radio noise floor. It is shown that broadband turbine RFI would be at a level below the noise floor at Hartlen Point when the turbine is located at a range of 300 meters from the radar receive array. The second effect is the scattering of radar signals by the rotating turbine blades. Simple calculations are carried out to determine the Radar Cross-Section (RCS) of the blades. This RCS varies with the rotation of the blades. Thus the apparent blade RCS will vary slowly in time such that radar clutter signals will be modulated and spread into regions of the range-Doppler plane that are normally free of clutter. The calculations suggest that the Doppler spreading may be significant if the turbine is less than 1.5 km from the radar.

Résumé

On effectue une étude des effets qu'exercerait une éolienne sur un système radar haute fréquence à ondes de surface susceptible d'être installé à Hartlen Point (Nouvelle-Écosse). La portée de l'étude est limitée au modèle d'éolienne V-47 produit par Vestas Wind Systems. L'étude porte sur deux effets exercés par l'éolienne sur le radar. Le premier effet est la production de brouillage radioélectrique (RFI) par l'éolienne. Des mesures effectuées pour une éolienne en place permettent de déterminer l'existence d'une limite supérieure en ce qui concerne l'apport de l'éolienne au plancher de bruit radioélectrique local. On montre que le niveau de RFI à large bande causé par l'éolienne serait inférieur au plancher de bruit à Hartlen Point lorsque l'éolienne est située à une distance de 300 mètres du réseau de réception du radar. Le deuxième effet est la dispersion des signaux radar par les pales tournantes de l'éolienne. Des calculs simples sont effectués pour déterminer la surface équivalente radar (SER) des pales. Cette SER varie avec la rotation des pales. Ainsi, la SER apparente des pales varie lentement en fonction du temps, de sorte que les échos parasites radar sont modulés et étalés dans des régions du plan distance-Doppler qui sont normalement exemptes d'échos parasites. Les calculs portent à croire que l'étalement Doppler peut être important lorsque l'éolienne est située à moins de 1,5 km du radar.

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Executive summary

Effects of Wind Turbines on High Frequency Surface Wave Radar

R. J. Riddolls; DRDC Ottawa TM 2005-240; Defence R&D Canada – Ottawa;
December 2005.

This memorandum documents a study of the effects of wind turbines on a potential High Frequency Surface Wave Radar system at Hartlen Point, Nova Scotia. The scope of the study is limited to the model V-47 wind turbine produced by Vestas Wind Systems. The study considers two effects of the turbine on the radar. The first effect is the production of Radio Frequency Interference (RFI) by the turbine. The second effect is the scattering of radar signals by the rotating turbine blades.

With regards to the production of RFI by the turbine, if the level of RFI exceeds the background noise floor of the environment in which the radar operates, then the ability of the radar to detect targets will be significantly degraded. To assess turbine RFI levels, measurements were carried out in the vicinity of an existing V-47 turbine located near Goderich, Ontario. Measurements determine an upper bound on the contribution of the turbine to the radio noise floor. It is shown that this upper-bound RFI is below the noise floor at Hartlen Point when the turbine is located at a range of 300 meters from the radar receive array.

As for scattering of radar signals by the rotating turbine blades, some simple calculations are carried out to determine the Radar Cross-Section (RCS) of the blades. This RCS varies with the rotation of the blades. Thus the apparent blade RCS will vary slowly in time such that radar clutter signals will be modulated and spread into regions of the range-Doppler plane that are normally free of clutter. The calculations suggest that the Doppler spreading may be significant if the turbine is less than 1.5 km from the radar. For a turbine at 300 meters range from the radar, there is risk that scattering will reduce the ability of the radar to detect targets. No experiment has been carried out to specifically confirm this effect or its impact, and thus, an experiment is suggested for future work.

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Sommaire

Effects of Wind Turbines on High Frequency Surface Wave Radar

R. J. Riddolls; DRDC Ottawa TM 2005-240; R & D pour la défense Canada – Ottawa; décembre 2005.

Le présent document étaye une étude des effets qu'exerceraient des éoliennes sur un système radar haute fréquence à ondes de surface susceptible d'être construit à Hartlen Point (Nouvelle-Écosse). La portée de l'étude est limitée au modèle d'éolienne V-47 produit par Vestas Wind Systems. L'étude porte sur deux effets exercés par l'éolienne sur le radar. Le premier effet est la production de brouillage radioélectrique (RFI) par l'éolienne. Le deuxième effet est la dispersion des signaux radar par les pales tournantes de l'éolienne.

En ce qui concerne la production de RFI par l'éolienne, si le niveau de RFI dépasse le plancher du bruit de fond du milieu dans lequel le radar est utilisé, la capacité de ce dernier à détecter des cibles sera réduite de façon appréciable. Dans le but d'évaluer les niveaux de RFI produits par l'éolienne, des mesures ont été effectuées à proximité d'une éolienne V-47 en place près de Goderich (Ontario). Les mesures permettent de déterminer l'existence d'une limite supérieure en ce qui concerne l'apport de l'éolienne au plancher de bruit radioélectrique. On montre que ce niveau de RFI présentant une limite supérieure est inférieur au plancher de bruit à Hartlen Point lorsque l'éolienne est située à une distance de 300 mètres du réseau de réception du radar.

En ce qui concerne la dispersion des signaux radar par les pales tournantes de l'éolienne, des calculs simples sont effectués pour déterminer la surface équivalente radar (SER) des pales. Cette SER varie avec la rotation des pales. Ainsi, la SER apparente des pales varie lentement en fonction du temps, de sorte que les échos parasites radar sont modulés et étalés dans des régions du plan distance-Doppler qui sont normalement exemptes d'échos parasites. Les calculs portent à croire que l'étalement Doppler peut être important lorsque l'éolienne est située à moins de 1,5 km du radar. Dans le cas d'une éolienne située à 300 mètres du radar, la dispersion risque de réduire la capacité du radar à détecter les cibles. Aucune expérience n'a été effectuée dans le but de confirmer précisément cet effet ou ses répercussions ; par conséquent on propose l'exécution d'une expérience dans le cadre des travaux futurs.

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1 Introduction

In this memorandum we examine the effects of wind turbines on High Frequency Surface Wave Radar (HFSWR). The motivation for the work is to provide comment on the suitability of locating a wind turbine at a range of approximately 300 m with respect to a potential HFSWR installation at Hartlen Point, Nova Scotia. This study is limited in scope to the model V-47 wind turbine manufactured by Vestas Wind Systems. We consider two effects of this turbine on radar performance. The first is the production of harmful Radio Frequency Interference (RFI) by the turbine. The second is the scattering of radar signals by the wind turbine towers and the rotating turbine blades.

Some investigation into the effect of RFI can be made by conducting field measurements in the vicinity of an existing V-47 wind turbine. In a field measurement, the turbine-produced RFI will be superposed with other man-made emissions as well as atmospheric noise. Man-made sources are generally characterized by devices that produce transient currents and/or air ionization, such as switching power supplies, electrical brushes, spark plugs, arc welders, and high-voltage power lines. Atmospheric noise arises from the worldwide propagation of emissions from lightning-produced air ionization. Due to this superposition of sources, the level of turbine-produced RFI cannot be determined precisely. However, an upper bound on the level of RFI from the turbine can be determined by assuming the worst case that all of the measured signals result from the turbine. This upper bound can then be inverse-square scaled with distance and compared to the known noise floor at a candidate radar site to determine if turbine-produced RFI could possibly impact radar performance.

The problem of scattering of radar signals by wind turbines is also considered in this study. Since there are currently no turbines in Canada that are co-located with HF radar systems, this problem could be addressed either theoretically or by building a temporary HF transmitter near a wind turbine and conducting measurements of the scattered signals. Due to limitations of time, the problem was examined theoretically in terms of the instantaneous Radar Cross-Section (RCS) of rotating turbine blades. No attempt has been made to examine all combinations of antenna beam patterns and turbine blade orientations. Only the worst case scenario of broadside scattering from cylindrical structures is considered in this study. The cross section calculations follow from well-established electromagnetic field solutions near conducting and dielectric cylinders.

2 Radio frequency interference

The proposed wind turbine is a Vestas Wind Systems model V-47. This particular turbine uses an asynchronous (induction) generator and is attached directly to the electrical grid. As a consequence, the rotor velocity must be controlled within a few percent of the synchronous velocity to maintain consistent torque. This control is done by blade pitch regulation and electronic adjustment of a resistance in series with the generator. This generator configuration does not depend on AC/DC power conversion or electrical brushes, and thus at an intuitive level, one does not expect significant levels of RFI to be produced. However, this may not be the case for other Vestas turbine models. For example, the model V-66 turbine uses AC/DC/AC conversion to allow variable rotor velocity, and thus one might be faced with significant RFI.

Intuition notwithstanding, a measurement was made to assess the RFI emission levels of the V-47. An existing V-47 turbine was located on the eastern shore of Lake Huron, near Goderich, Ontario. A photograph of the turbine is in Figure 1. The diameter of the 3-blade rotor in the photograph is 47 meters. A radio receiver was used to measure the RFI in the vicinity of the turbine on 19 Nov 2005 during the hours 1000–1400, when the atmospheric noise level was at a minimum. During the measurements, the rotor was turning at a rate of 30 revolutions per minute.

Figure 1: *The Vestas V-47 wind turbine at Goderich, Ontario.*

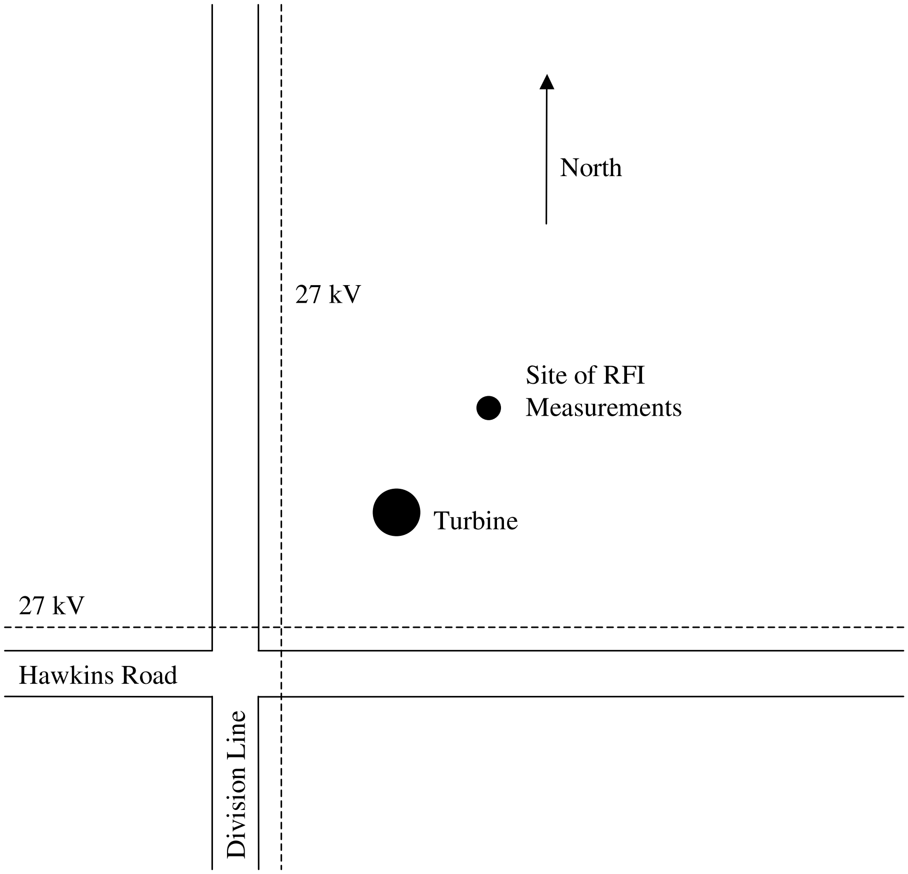

Figure 2: *Site of Vestas V-47 at Goderich, Ontario (not to scale).*

As mentioned in Section 1, a difficulty in determining turbine RFI lies in isolating the turbine-produced RFI from the other radio noise sources in the environment. In particular, wind turbines are usually co-located with high-voltage power lines, which can produce HF radio noise by coronal discharge (ionization of air around the wire), or spark gap discharge (arcing across imperfect wire insulators). A map of the turbine site at Goderich is shown in Figure 2. There are currently 27-kV power lines that run along both Hawkins Road and Division Line. A good site for maximizing turbine RFI reception relative to power line noise is to the northeast of the turbine. The chosen site is about 100 meters from the turbine, and about 150 meters from the power lines. Permission was obtained from a local farmer to deploy a radio receiver at this location. The measured noise floor at this location establishes an upper bound on the noise produced by the turbine, which can then be inverse-square scaled to predict an upper bound on the turbine-produced noise floor at other locations.

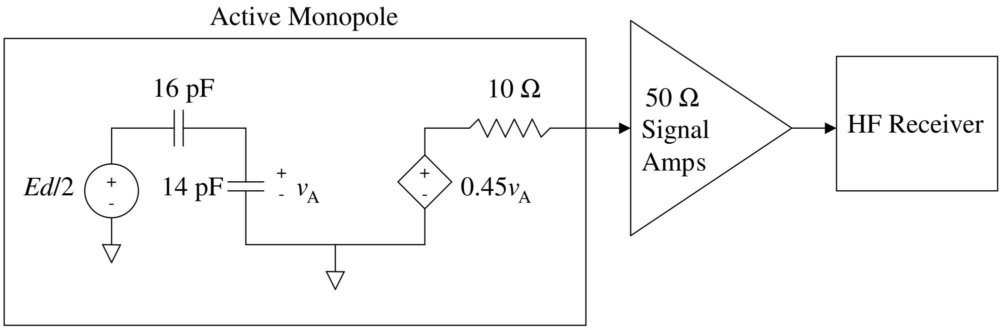

Figure 3: *Measurement apparatus.*

The measurement apparatus consists of a vertical 1-m monopole active antenna (Antenna Design and Manufacturing Corporation, model EFA110/OD), three series-connected 10-dB signal amplifiers (Anzac Electronics, model AM-109), and an HF software-defined receiver (RFSpace Incorporated, model SDR-14). The measurement apparatus is shown in Figure 3. The antenna consists of a vertical conducting cylinder with a capacitance to ground of 16 pF. The input capacitance of the active monopole circuit is 14 pF. The RMS vertical component E of the incident RFI electric field forms a voltage $Ed/2$ on the cylinder, where d is the length of the cylinder. This voltage appears across the series combination of the cylinder capacitance to ground and the input capacitance of the active monopole circuit. The voltage v_A at the 14-pF input to the circuit is $0.233Ed$. The gain of the active monopole circuit is 0.450, and the output impedance is 10 Ω. The voltage developed on the 50-Ω input to the signal amplifiers is $0.0875Ed$. The gain of the three series-connected 10-dB amps is 37.5, and the voltage applied to the 50-ohm input of the receiver is $3.28Ed$.

The recorded noise floor at the RFI measurement site is shown in Figure 4. This noise floor is determined by finding the average of 100 FFTs of the field E sampled at 66.667 MHz, and plotting the minimum power level observed in each 100-kHz bin. The vertical scale of the plot is expressed in terms of f_a, which represents signal power in dB above thermal noise κTB, where κ is Boltzmann's constant, T is temperature, B is bandwidth of the measurement, and the measuring device is a conjugate-matched (non-active) electrically short vertical monopole over an ideal ground plane. It can be shown from antenna theory that f_a is related to E in SI units by

$$f_a = 10\log_{10}\left(\frac{3c^2E^2}{16\pi\eta f^2\kappa TB}\right), \tag{1}$$

where c is the speed of light, η is the impedance of free space, and f is the frequency of the measurement. Sometimes this formula is recast in a version that is suited for

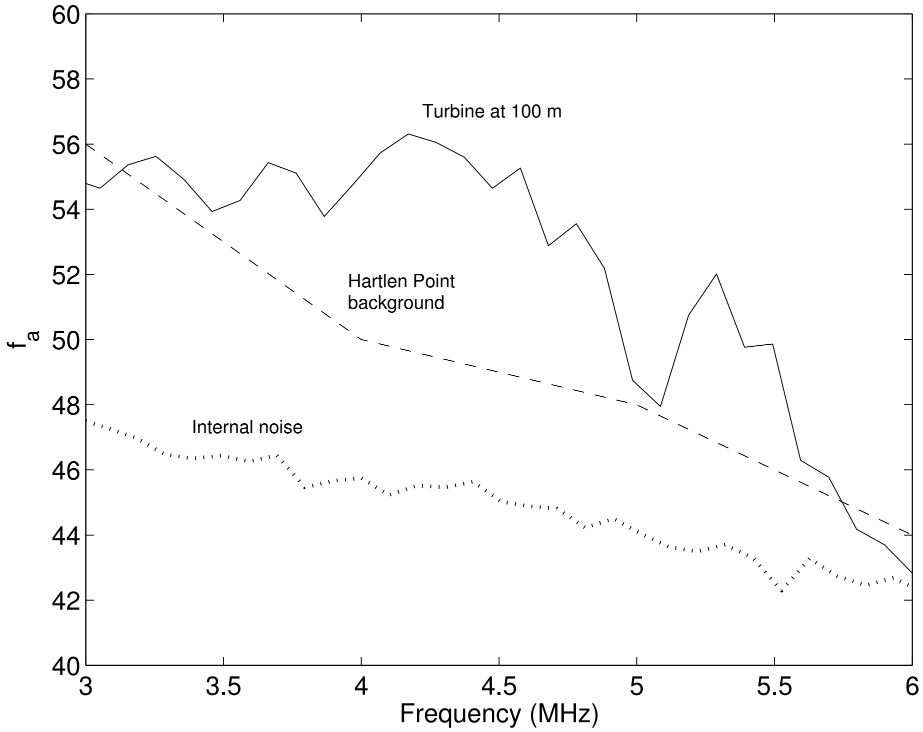

Figure 4: *Solid line: measured noise floor at 100 m from turbine. Dashed line: measured noise floor at Hartlen point. Dotted line: measured internal noise of apparatus.*

hand calculation. If we take E in μV/m, B in Hz, and f in MHz, and $T = 290$ K, then one can write the above formula in the form [1]

$$f_a = 20 \log_{10} E - 10 \log_{10} B - 20 \log_{10} f + 95.5. \tag{2}$$

In Figure 4, the solid line is the measured noise floor at 100 m from the turbine, the dashed line is the noise floor at Hartlen Point [2], and the dotted line is the internal noise of the receiver apparatus as determined by shorting the antenna to ground. The first observation is that the apparatus is externally noise limited, such that the measured noise floor (solid line) exceeds the internal noise of the device (dotted line). The second observation is that the measured noise floor can be regarded as an upper bound on the RFI from the turbine at 100-m range. Locating a turbine 300 m away from the radar would result in an inverse-square propagation attenuation of 10 dB. This attenuation would be sufficient to put the upper bound on the turbine-produced RFI below the measured Hartlen Point noise floor (dashed line). Therefore we conclude from these measurements that the RFI produced by the V-47 wind turbine, if any, should be low enough so as not to significantly influence HFSWR target detection performance at Hartlen Point.

3 Scattering

The second effect that is considered in this study is the scattering of radar signals by the wind turbine. This problem was studied in a report [3] relevant to air traffic control microwave radar. Some of the mechanisms considered were:

1. The wind turbine towers act as large radar targets, with an RCS of typically 60 dBm^2. The metal surfaces represent a significant aperture in terms of wavelength. The large signals associated with echoes from turbine towers may overload the radar receivers.
2. The rotating wind blades represent moderate (30 dBm^2) radar targets with velocities comparable to air targets. These could lead to superfluous radar hits that could confuse the tracker.
3. The rotating wind blades represent a time-varying RCS and may serve to modulate the radar transmit and/or receive beams, leading to a spreading of radar echoes in Doppler.

In the context of HFSWR, mechanisms 1 and 2 are insignificant. The reasoning is that in the HF band (3-30 MHz), the RCS of the towers is sufficiently low that the receivers are not overloaded. Furthermore, HFSWR typically has a near-range eclipsing zone of about 50 km in extent, which would exclude most land-based wind turbine targets. However, the third mechanism is problematic for HFSWR as the beam modulation rate is on the order of the typical Doppler shifts observed by the radar. At times when a wind turbine blade is oriented roughly normal (broadside) to the radar signal wavenumber $\mathbf{k}$, there is significant scatter of radar signals from the blade. This state occurs every 60 degrees of rotation of the turbine rotor—approximately a 3-Hz rate.

The V-47 turbine blades are composed of a hollow shell of fiberglass-reinforced polyester. Within the dielectric shell of the blade, there exists a conducting wire for the purpose of lightning protection. The Canadian Standards Association standard CAN/CSA-B72-M87 specifies that this wire must be at least 4 mm in radius (#6 American Wire Gauge). We now determine the RCS of these structures, following [4].

At HF it is permissible to model the turbine blades and the lightning conductor as cylinders. We begin with the simplest case of an infinitely long cylinder of radius a, oriented in the $\hat{\mathbf{z}}$ direction of a cylindrical set of coordinates (ρ, ϕ, z). Consider an incident plane wave $\mathbf{E}_0$ polarized along the cylinder axis:

$$\mathbf{E}_0 = \hat{\mathbf{z}} E_{0z} = \hat{\mathbf{z}} E e^{ik\rho\cos\phi}, \tag{3}$$

where k is the free space wavenumber. This plane wave can be rewritten in terms of cylindrical eigenfunctions of the wave equation using the generating function

$$e^{\xi(t-1/t)/2} = \sum_{n=-\infty}^{\infty} t^n J_n(\xi), \tag{4}$$

where J_n is the ordinary Bessel function of order n. Setting $t = ie^{i\phi}$, we can rewrite Equation (3) as

$$E_{0z} = E \sum_{n=-\infty}^{\infty} i^n J_n(k\rho) e^{in\phi}. \tag{5}$$

The scattered fields would consist of $\hat{\mathbf{z}}$-polarized waves inside and outside the cylinder, denoted by $\mathbf{E}_1 = E_{1z}\hat{\mathbf{z}}$ and $\mathbf{E}_2 = E_{2z}\hat{\mathbf{z}}$, respectively. The scattered field inside the cylinder must be bounded at the origin, thus we choose cylindrical wave equation solutions of the form

$$E_{1z} = \sum_{n=-\infty}^{\infty} a_n J_n(k_1\rho) e^{in\phi}, \tag{6}$$

where $k_1 = \omega\sqrt{\mu_0 \epsilon}$, and ϵ is the cylinder dielectric permittivity. The scattered field outside the cylinder can be written in terms of outward propagating cylindrical waves:

$$E_{2z} = \sum_{n=-\infty}^{\infty} b_n H_n^{(1)}(k\rho) e^{in\phi}, \tag{7}$$

where $H_n^{(1)}$ is the nth-order Hankel function of the first kind. The tangential components of the magnetic fields $\mathbf{H}_0$, $\mathbf{H}_1$, and $\mathbf{H}_2$ associated with the above electric fields are found from Maxwell's equations:

$$\begin{aligned}
H_{0\phi} &= \frac{ikE}{\omega\mu_0} \sum_{n=-\infty}^{\infty} i^n J_n'(k\rho) e^{in\phi} && (8)\\
H_{1\phi} &= \frac{ik_1}{\omega\mu_0} \sum_{n=-\infty}^{\infty} a_n J_n'(k_1\rho) e^{in\phi} && (9)\\
H_{2\phi} &= \frac{ik}{\omega\mu_0} \sum_{n=-\infty}^{\infty} b_n H_n^{(1)\prime}(k\rho) e^{in\phi}. && (10)
\end{aligned}$$

The coefficients a_n and b_n can be found by applying the boundary condition that the tangential electric and magnetic fields are continuous at the surface of the cylinder:

$$\begin{aligned}
\left(E_{0z} + E_{2z}\right)_{\rho=a} &= \left(E_{1z}\right)_{\rho=a} && (11)\\
\left(H_{0\phi} + H_{2\phi}\right)_{\rho=a} &= \left(H_{1\phi}\right)_{\rho=a}. && (12)
\end{aligned}$$

Solving for the coefficients yields the relations

$$a_n = \frac{i^n E J_n(ka) + b_n H_n^{(1)}(ka)}{J_n(k_1 a)} \tag{13}$$

$$b_n = i^n E \frac{k_1 J_n(ka) J_n'(k_1 a) - k J_n'(ka) J_n(k_1 a)}{k H_n^{(1)'}(ka) J_n(k_1 a) - k_1 H_n^{(1)}(ka) J_n'(k_1 a)}, \tag{14}$$

where the prime indicates differentiation. The scattered fields from an infinite cylinder of arbitrary radius can then be determined by substituting these coefficients into Equations (5) through (7).

We now specialize to the cases of two limits. The first is the case of thin highly conducting cylinders, where $ka \ll 1 \ll k_1 a$. The second is the case of thin dielectric cylinders, where $ka, k_1 a \ll 1$. In both cases, it can be shown that only the $n = 0$ terms are significant. For the thin highly conducting cylinder case, we have

$$b_0 \approx \frac{i\pi E}{2\log(\gamma ka/2)}, \tag{15}$$

where $\log \gamma = 0.5772$. In the thin dielectric cylinder case, the result is

$$b_0 = \frac{i\pi E (ka)^2}{4} \left(\frac{k_1^2}{k^2} - 1 \right). \tag{16}$$

In arriving at these results, the following small argument approximations are used:

$$J_0(\xi) \approx 1 \qquad H_0^{(1)}(\xi) \approx iY_0(\xi) \approx 2i \log(\gamma\xi/2)/\pi \tag{17}$$

$$J_0'(\xi) \approx -\xi/2 \qquad H_0^{(1)'}(\xi) \approx iY_0'(\xi) \approx 2i/(\pi\xi). \tag{18}$$

We would like to find the scattered field of a finite cylinder of length L. An approximate method is to evaluate the solutions above on a finite-length cylinder surface, and use Huygens' principle to find the scattered field. Cylinder end contributions are ignored. We use the Franz formula [5], which gives a scattered field $\mathbf{E}_s$ at an observation location $\mathbf{r} = r\hat{\mathbf{r}}$ in terms of the integral of the field on the surface of the cylinder:

$$\mathbf{E}_s(\mathbf{r}) = \nabla \times \iint dS'\, g(\mathbf{r}, \mathbf{r}')\, \hat{\mathbf{n}} \times \mathbf{E}_2(\mathbf{r}') + \frac{i}{\omega\epsilon_0} \nabla \times \nabla \times \iint dS'\, g(\mathbf{r}, \mathbf{r}')\, \hat{\mathbf{n}} \times \mathbf{H}_2(\mathbf{r}'), \tag{19}$$

where $\hat{\mathbf{n}}$ is a unit normal to the cylinder surface and $g(\mathbf{r}, \mathbf{r}')$ is the freespace Green's function:

$$g(\mathbf{r}, \mathbf{r}') = \frac{e^{ik|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|}. \tag{20}$$

In the limits $ka \ll 1$ (thin cylinder) and $kr \gg 1$ (far field), we find that

$$\nabla \approx ik\hat{\mathbf{r}} \qquad g(\mathbf{r}, \mathbf{r}') \approx \frac{e^{ik(r - z'\cos\theta)}}{4\pi r}, \tag{21}$$

where z' is the z coordinate of the surface field along the axis of the cylinder, and θ is the polar angle. Furthermore, the dominance of the $n = 0$ terms of Equations (5) through (10) in the thin cylinder limit implies that all the fields are azimuthally uniform. Thus the fields can be removed from the integrals in Equation (19), and the integrals evaluated as follows:

$$\iint dS' g(\mathbf{r}, \mathbf{r}') = \frac{aLe^{ikr} \operatorname{sinc} \delta}{2r}, \tag{22}$$

where $\operatorname{sinc} \delta = (\sin \delta)/\delta$, with $\delta = (kL/2) \cos \theta$. The scattered field is

$$\mathbf{E}_s \approx -\frac{ik^2 aLe^{ikr} \operatorname{sinc} \delta}{2\omega\epsilon_0 r} \hat{\mathbf{r}} \times \hat{\mathbf{r}} \times \hat{\mathbf{n}} \times (\mathbf{H}_2)_{\rho=a}. \tag{23}$$

In the thin highly conducting cylinder case, we find that

$$\mathbf{E}_s \approx -\hat{\boldsymbol{\theta}} \frac{ELe^{ikr} \operatorname{sinc} \delta \sin \theta}{2r \log(\gamma ka/2)}. \tag{24}$$

In the thin dielectric cylinder case, we similarly find that

$$\mathbf{E}_s \approx -\hat{\boldsymbol{\theta}} \frac{EL(ka)^2 (N^2 - 1) e^{ikr} \operatorname{sinc} \delta \sin \theta}{4r}, \tag{25}$$

where N is the dielectric refractive index. The RCS is given by

$$\sigma = 4\pi r^2 \frac{|\mathbf{E}_s|^2}{|\mathbf{E}_0|^2}. \tag{26}$$

Inserting Equation (24) into Equation (26) and taking $|\mathbf{E}_0| = E$, we find that the RCS of the conducting thin cylinder is given by

$$\sigma = \frac{\pi L^2 \operatorname{sinc}^2 \delta \sin^2 \theta}{\log^2(\gamma ka/2)}. \tag{27}$$

At $\theta = \pi/2$ and 4 MHz ($k = 0.084$ 1/m), the RCS of a 23-meter conducting wire 4 mm in radius is approximately 25 m^2. In the case of the thin dielectric cylinder, we combine Equations (24) and (26) to find that the RCS is

$$\sigma = \frac{\pi L^2 (ka)^4 (N^2 - 1)^2 \operatorname{sinc}^2 \delta \sin^2 \theta}{4}. \tag{28}$$

If one models the V-47 blades as cylinders 23 m in length, 1 m in radius, and composed of solid fiberglass ($N \approx 2.7$), then the RCS at $\theta = \pi/2$ and 4 MHz is about 1 m^2. This is an overestimate since the actual blade is a fiberglass shell. However, it is still much less than the RCS of the lightning conductor wire. Thus we will assume that

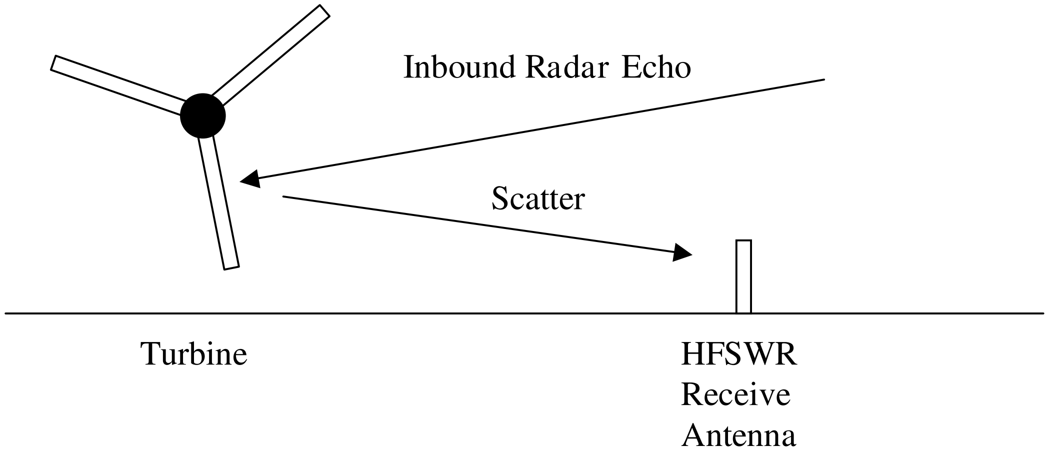

Figure 5: *Modulation of receive beam by turbine scatter.*

the RCS of the turbine blade is dominated by the RCS associated with the lightning conductor.

Let us now consider the effect of periodic broadside illumination of turbine blades by radar echoes, as shown in Figure 5. An inbound target echo propagates past the HFSWR receive antenna, scatters from the rotating turbine blades, and is then captured by the HFSWR receive antenna. Note than an analogous process occurs with respect to the transmitted radar signal, with substantially similar results. The scattering process suggested in Figure 5 serves to modulate the radar echo at a 3-Hz rate corresponding to the rate at which the blades (and thus the lightning conductor wires) rotate to a position normal to the wavenumber **k** of the incoming radar echo. This modulation effectively introduces a spreading in Doppler of radar sea and ionospheric clutter, with possible impact on radar detection performance depending on the severity of the spreading. The intensity of the turbine-modulated signal can be roughly estimated by multiplying the power flux of an inbound target echo by the RCS of the turbine blade, and attenuating the scattered signal appropriately for the distance between the turbine and the radar. In other words,

$$\Gamma_s = \frac{\Gamma\sigma}{4\pi R^2}, \tag{29}$$

where Γ is the inbound radar echo power flux, σ is the maximum blade RCS, R is the distance between the blade and the HFSWR receive antenna, and Γ_s is the power flux of the turbine-scattered radar echo. Radar clutter echoes routinely achieve signal-to-noise ratios of 60 dB in the case of HFSWR [6]. Thus to ensure no significant effect resulting from turbine-modulation of radar echoes, one must require that $\Gamma_s/\Gamma < 10^{-6}$.

Using $\sigma = 25$ m^2 as an upper bound RCS in Equation (29), meeting this condition would require the turbine to be about 1.5 km away from the radar. Therefore we conclude on the basis of the above considerations that a rotating turbine 300 m from the radar may generate Doppler spreading of radar signals with possible impact on target detection performance.

4 Conclusions

Measurements show no evidence that the V-47 wind turbine produces RFI that would significantly affect an HFSWR located 300 meters from the turbine in a radio noise environment similar to that of Hartlen Point. This conclusion is made on the basis of measured noise floor levels in the vicinity of an existing V-47 wind turbine.

However, simple calculations suggest that signal scattering by nearby turbine blades could cause significant Doppler spreading of sea and ionospheric clutter if the turbine is less than 1.5 km from the radar. No experiment has been carried out to specifically confirm this effect or its impact. Thus placing a turbine less than 1.5 km in range from an HFSWR entails accepting risk that Doppler-spread clutter may influence the detection capability of the radar.

Finally, it should be noted that the above scattering mechanism could be investigated in future work by transmitting a long tone from a low-power HF transmitter near a wind turbine, and monitoring the power levels at ±3 Hz from the carrier using an HF receiver apparatus similar to that used in the RFI measurements.

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(U) A study is carried out on the effects of a wind turbine on a potential High Frequency Surface Wave Radar system at Hartlen Point, Nova Scotia. The scope of the study is limited to the model V-47 wind turbine produced by Vestas Wind Systems. The study considers two effects of the turbine on the radar. The first effect is the production of Radio Frequency Interference (RFI) by the turbine. Measurements of an existing wind turbine determine an upper bound on the contribution of the turbine to the local radio noise floor. It is shown that broadband turbine RFI would be at a level below the noise floor at Hartlen Point when the turbine is located at a range of 300 meters from the radar receive array. The second effect is the scattering of radar signals by the rotating turbine blades. Simple calculations are carried out to determine the radar cross-section (RCS) of the blades. This RCS varies with the rotation of the blades. Thus the apparent blade RCS will vary slowly in time such that radar clutter signals will be modulated and spread into regions of the range-Doppler plane that are normally free of clutter. The calculations suggest that the Doppler spreading may be significant if the turbine is less than 1.5 km from the radar.

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SURFACE WAVE
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