Analysis of the Impact of Scattering from a Proposed Wind Farm in the Vicinity of the Stockbridge Test Facility

Abstract: The Stockbridge Test Facility was established in 1957 to provide an electromagnetically quiet environment to support U.S. Air Force research and development in command, control, communications, computing, and intelligence. The facility has been in continuous use since that time, and has recently been upgraded to provide a controllable contested environment. Recent experiments support U.S. Air Force, multi-service, and international collaborative research in communications data links, networking, spectrum sharing, and exploitation. A clean energy project has recently been proposed to establish a farm of wind turbine generators in the vicinity of the Stockbridge facility. This white paper provides an analysis of the impact of the proposed project on the electromagnetic environment, and establishes siting criteria for the minimization of the impact on Department of Defense research. The results indicate that reflections from the nearby proposed structures would compete strongly with signals under test. Reflections from structures of the proposed size located more than 7 nautical miles from the Stockbridge site would most likely have no significant effect. Structures placed between 3.5 nmi and 7 nmi would most likely impact higher power experiments in the upper frequency ranges, as well as moderate power experiments in the lower frequency bands. Proposed structures located within 3.5 nmi would most likely have impacted most tests conducted at the site within the past year.

1. Introduction:

The U.S. Air Force established the Stockbridge Test Facility more than 55 years ago [1] to support research and development important to the Department of Defense. Stockbridge was selected based on its line-of-sight to the Rome Research Site, and its location in a rural, electromagnetically quiet environment.

Recently, a clean energy project has been proposed to install a number of wind turbine generators in the vicinity of the Stockbridge facility. The wind turbines expected to be installed are 3 MW Acciona Wind AW 125 3.0 generators, with an expected hub height of 120 m, and an expected rotor diameter of 125 m, resulting in an overall tip height of 182.5 m [2].

Most concerns expressed to date have regarded flight operations and the potential to obstruct line-of-sight communications links between Stockbridge and the Rome Research Site and Newport Test Facility. Not addressed so far has been the potential impact of the project on calibrated radio frequency measurements taken during laboratory research experiments. Such experiments are a primary purpose for maintaining the Stockbridge facility, and the impact of the proposed project on those experiments needs to be considered.

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The Stockbridge facility is contained within a 300+ acre parcel on a hill in the Town of Stockbridge, Madison County, N.Y. A number of concrete test pads with shelters, power, and communications are located throughout the site, as shown in Figure 1.

The proposed green energy project would erect a number of wind turbine generators roughly along a northwest to southeast line on the same ridge as the Stockbridge facility. The proposed locations of the wind turbine generators are shown in Figure 2.

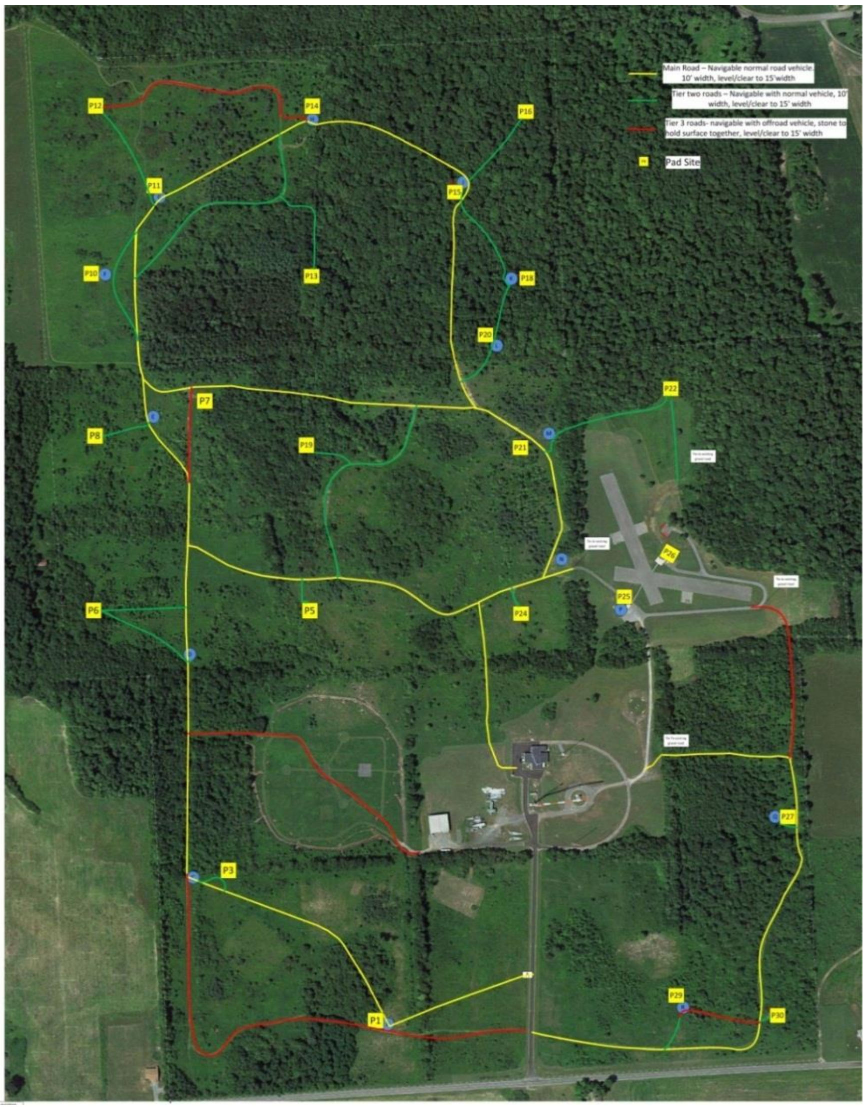

Figure 1: Plan view of the Stockbridge Test Facility

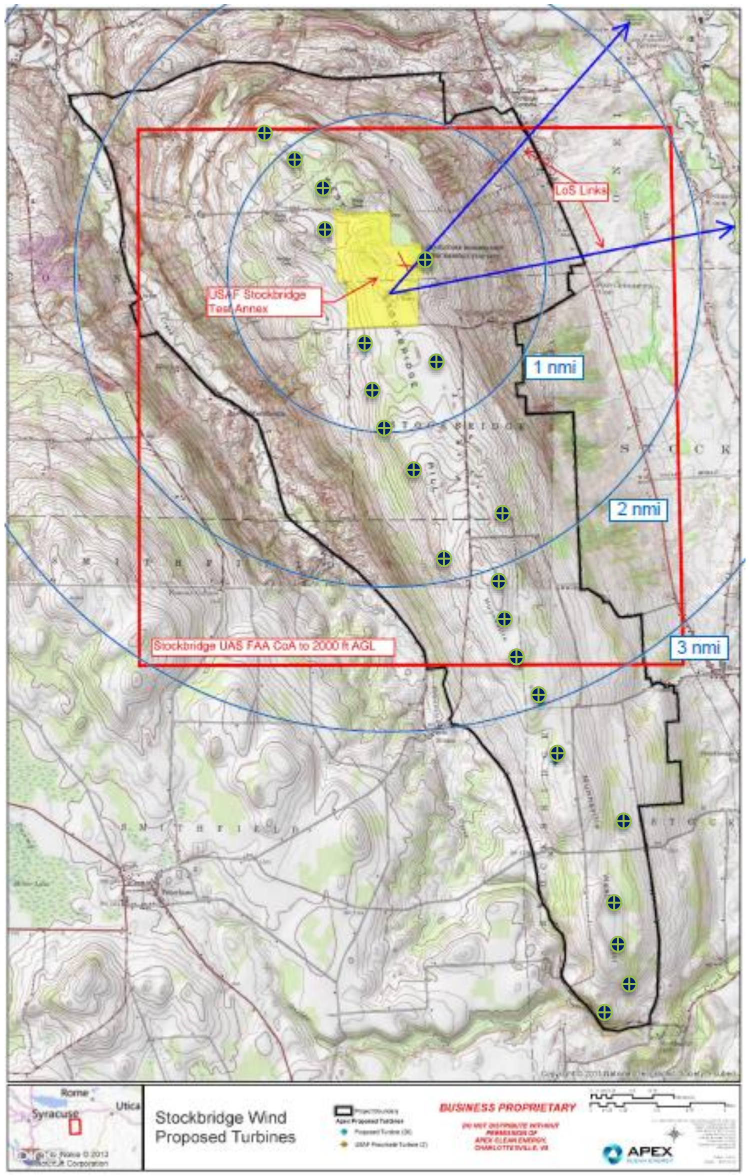

Figure 2: Locations of proposed wind turbine generators

The presence of large wind turbine generator structures in the vicinity of the Stockbridge facility has the potential to induce electromagnetic signals which interfere with sensitive radio frequency signals measured in laboratory research. This interference can include scattered returns (multipath) from single large structures, multi-bounce scattering from multiple structures, Doppler effects imparted from rotating blades, and electromagnetic fields produced from multi-Megawatt generators and their associated transmission lines.

This white paper examines the magnitude of signals scattered from the proposed wind turbine generators, and their potential interference on calibrated radio frequency measurements. The white paper also establishes turbine siting requirements to minimize the impact on Department of Defense research.

2. Line of sight distance:

Structures outside the radio frequency line of sight of the Stockbridge facility will have no potential to produce scattering that would interfere with laboratory measurements. The optical line of sight is determined by the straight line distance to the horizon from an observing platform. If both the observing point and the point being observed are elevated, the optical line of sight distance will be the sum of the distances to the horizon from both points. Specifically, the visual line of sight distance between two elevated points on a spherical earth will be:

$$D_{LOS} = \sqrt{2R_e h_1 + h_1^2} + \sqrt{2R_e h_2 + h_2^2} \ , \qquad (\ )$$

where h_1 is the height of the receiver, h_2 is the height of the wind turbine generator and R_e is the radius of the earth (6371.0 km).

The structures in the proposed project would extend to a height of 182.5 m. If a receiver is placed on the ground, some portion of the structures would be in the visible line of sight to the receiver at a range of more than 48 km. The tower alone, at a height of 120 m, would be in the line of sight distance out to a range of 39 km.

All of the wind turbine generators in the proposed project would be in the optical line of sight of the Stockbridge facility, unless the line of sight is blocked by intervening terrain. The interference caused by scattering from these structures will depend upon the magnitude of the scattered signals. The scattered signals will have no impact if they are sufficiently small.

3. Ambient background interference:

It is presumed that reflected signals which fall below the ambient background interference will have no significant effect on laboratory research. The thermal noise power is given by [3]:

$$N = kT_0 BF_n \quad , \qquad (1)$$

where: k = Boltzmann's constant (1.38 x 10-23 joules/K),
T_0 = Absolute zero (293 °K)
B = noise bandwidth
F_n = receiver noise figure

Assuming a typical signal bandwidth of 33 kHz and receiver noise figure of 3 dB, the computed thermal noise power would be -126 dBm.

However, thermal noise is often not the limiting factor on performance, but rather the total background interference, which includes ambient background radio frequency signals and measurement equipment limitations, as well as thermal noise. Figure 3 shows actual background interference plus noise as a function of frequency, measured on June 26, 2014 at the Stockbridge facility. The measurements show some known signals in the crowded UHF frequency band, and an ambient interference power level of approximately –105 dBm.

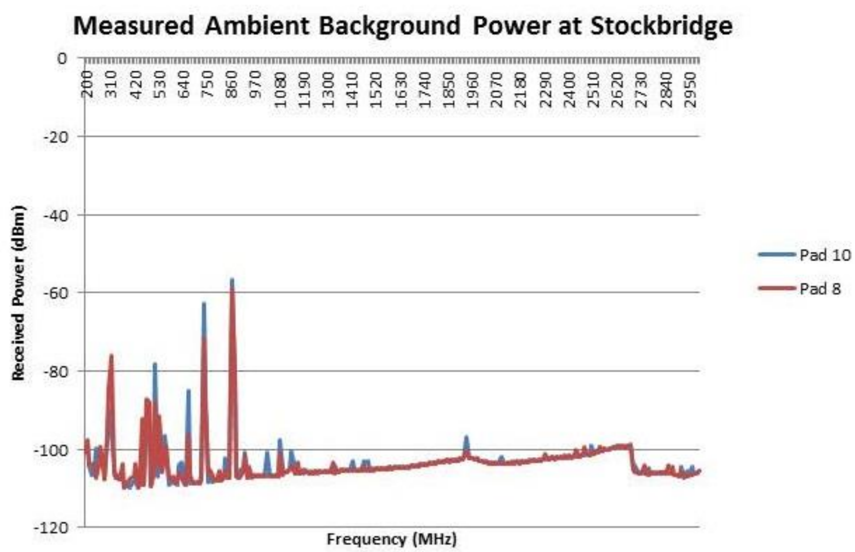

Figure 3: Measured ambient background level at the Stockbridge facility as a function of frequency. Average ambient interference power is approximately –105 dBm.

4. Desired signal level

In a typical experiment at the Stockbridge facility, a transmitter is located at one test pad and a receiver is located at another. A signal transmitted with power P_T through antenna with gain G_t will spread according the inverse square law, such that the power density at range R will be:

$$P_{density} = \frac{P_T G_T}{4\,\pi\,R^2}\,. \tag{2}$$

This power density is captured with an antenna of area A_R at the receive site, resulting in received power:

$$P_R = \frac{P_T G_T}{4\,\pi\,R^2} \times A_R\,. \tag{3}$$

Using the well-known relationship between antenna area and gain,

$$G = \frac{4\,\pi\,A}{\lambda^2}\,, \tag{4}$$

Equation (3) can be re-written as [4]:

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\,\pi)^2\,R^2}\,. \tag{5}$$

5. Scattered interference

Signals reflected from structures in the vicinity of a signal under test are called multipath. These signals combine in the receiver with the desired signal, either constructively or destructively, and can cause amplitude and phase distortion, fading, time spreading, and intersymbol interference. The rotating blades of a wind turbine generator can also induce Doppler effects, causing a spreading and time-varying frequency response of the signal under test. In these ways, multipath can interfere with the measurement of the signal under test. However, if the power levels of the scattered signals are low enough, they will not have an appreciable effect on the signal under investigation.

In a manner similar to Section 3, a signal transmitted with power P_T through antenna with gain G_T will spread according the inverse square law, such that the power density on a structure at distance d_1 will be:

$$P_{density\_tower} = \frac{P_T G_T}{4\,\pi\, d_1^2} \quad . \tag{6}$$

This power density is captured by an effective area, σ_T , called the radar cross section, and the power then reflected towards the receive site is:

$$P_{reflected} = \frac{P_T G_T}{4\,\pi\, d_1^2} \times \sigma_T \quad . \tag{7}$$

Spreading according to the inverse square law results in a power density at the receiver at distance d_2 from the tower of:

$$P_{density\_receiver} = \frac{P_T G_T}{4\,\pi\, d_1^2} \times \frac{\sigma_T}{4\,\pi\, d_2^2} \quad . \tag{8}$$

This power density is then captured by the receive antenna of area A_R, so that reflections from the tower are received with power

$$P_{tower} = \frac{P_T G_T}{4\,\pi\, d_1^2} \times \frac{\sigma_T}{4\,\pi\, d_2^2} \times A_R \ . \tag{9}$$

Using Equation (4) and combining terms results in [5]

$$P_{tower} = \frac{P_T G_T G_R \sigma_T \lambda^2}{(4\,\pi)^3\, d_1^2 d_2^2} \quad . \tag{10}$$

To ensure that the reflected power from the tower does not interfere with calibrated experimental results, this power level should be below the ambient interference level of -105 dBm, as described earlier.

6. Radar cross section

The radar cross section of wind turbine generators has received a great deal of attention in the past few years, both in the U.S. and internationally. The radar cross section of wind turbine generators depends on a number of factors including the dimensions and structure of the turbine component parts (tower, nacelle, blades), material composition, number and configuration of blades, wind direction, speed of rotation, nearby terrain, and electromagnetic far-field or near-field effects. A thorough analysis of radar cross section for a particular wind turbine generator in a particular location requires a detailed analysis using computational electromagnetics modeling tools. However, a reasonable estimate of radar cross section can be made using available measured data.

In 2006, the Air Force Research Laboratory (AFRL) Sensors Directorate performed a series of both detailed electromagnetic models and calibrated field measurements of commercial wind turbine generators. This work was performed in support of the Office of the Deputy Undersecretary of Defense (S&T), and a report summarizing the findings was delivered to a committee of the U.S. Congress [6].

The AFRL measurements were collected at the Fenner, N.Y. wind farm, located approximately 6 miles southwest of the Stockbridge facility. The Fenner wind farm consists of twenty 1.5 MW wind turbines manufactured by GE Wind Energy. Each turbine consists of a 65 m tower and a 3-bladed 70 m diameter rotor, with each blade 35 m in length. The total height of the structure, including tower and blades, is 100 m.

Figure 4, from the congressional report, summarizes the radar cross section of individual turbines over a wide range of frequencies. The data shows that at normal incidence, the radar cross section over all measured frequencies (L, S, X, and C bands) is approximately 32,000 square meters (45 dBsm).

However, the turbines measured at Fenner are approximately half the height of those proposed at Stockbridge. Since the radar cross section of the primary scattering component from the turbine (the cylindrical tower) varies as length-squared [7], the cross section of the Stockbridge towers can be expected to be larger by

$$10 \times log_{10}\left(\frac{182.5}{100}\right)^2 = 5.2\,dB \quad . \qquad (11)$$

With this adjustment, the radar cross section of a single wind turbine generator is expected to be 50 dBsm.

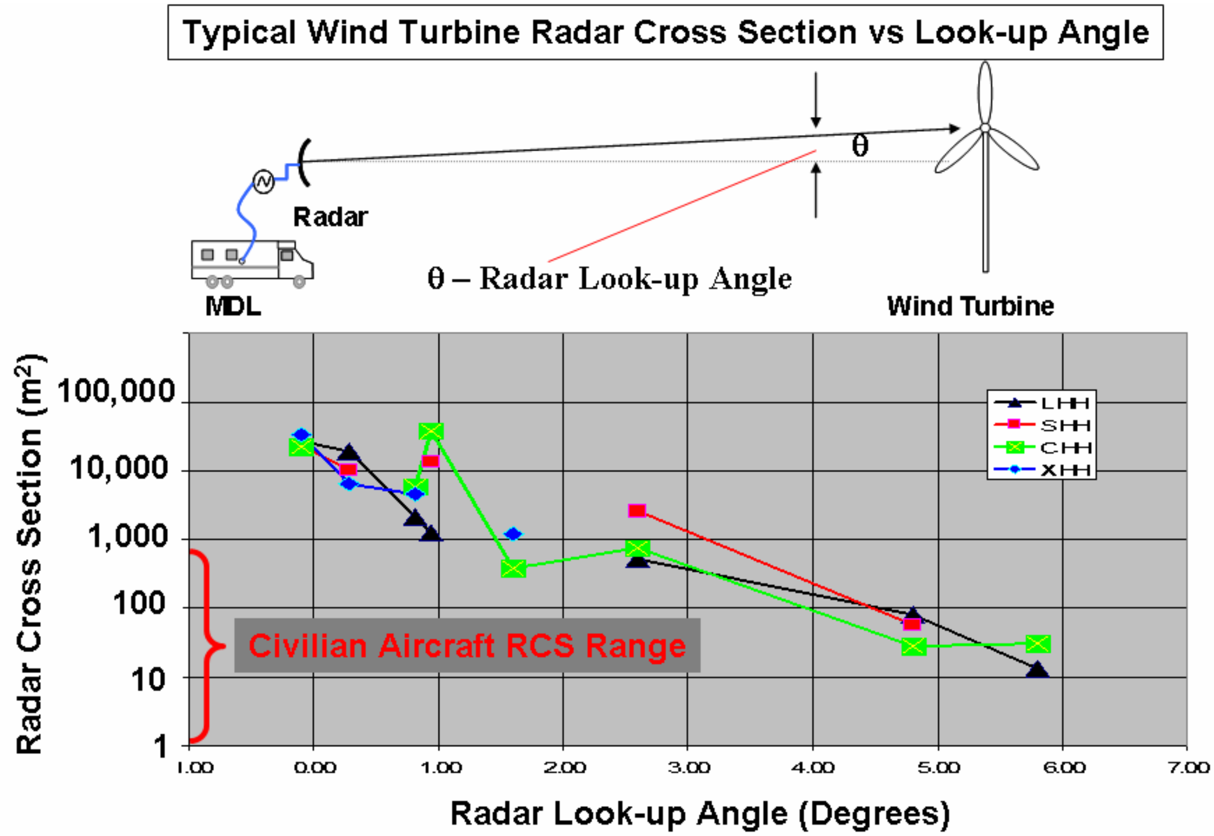

Figure 4: Summary of turbine radar cross section measurements from Fenner, NY wind farm [6].

7. Representative experimental configurations

As an experimental test station, the Stockbridge facility is used for the research and development of new and innovative command, control, communications, computing, and intelligence technologies. Therefore, there is not one, single test arrangement that encompasses all potential frequency, power, waveform, and antenna configurations used in testing.

This section considers typical experimental arrangements to determine the impact of scattered interference on calibrated RF measurements. For each of the representative configurations, the transmitter will be located at Pad 7, and the receiver located at Pad 3. Scattering will be computed from the nearest proposed wind turbine generator. This configuration is depicted in Figure 5.

<u>Typical L-band configuration</u>

Consider a typical experimental configuration which utilizes a signal generator to radiate 1 watt through an omnidirectional antenna, and where the signal is also received through an omnidirectional antenna. The desired and reflected signal levels can be computed using (5) and (10) above. Table 1 shows the calculation of the received power level of the desired direct path signal for an L-band experiment. The received signal level is calculated to be -59.9 dBm.

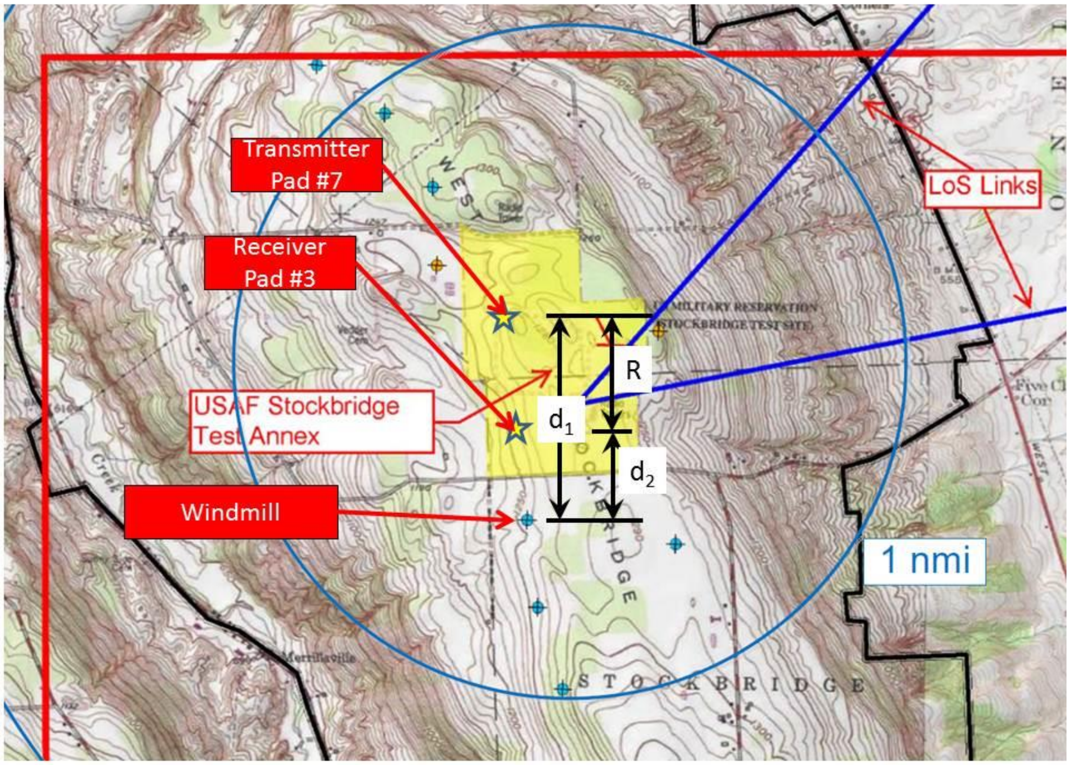

Figure 5. Representative experimental configuration. A transmitter is placed at Pad 7, and a receiver is located at Pad 3.

Table 1: Representative configuration parameters and calculation of desired signal level (L-band)

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\,\pi)^2\, R^2}$$

Parameter	Remarks	dB
P_T	transmit power, 1 watt	30 dBm
G_T	Transmit gain, omni	0
G_R	Receive gain, omni	0
λ^2	f = 1200 MHz; λ = 0.25 m	-12
$(4\pi)^2$	Constant	22
R^2	Range = 624 m	55.9
	P_R =	-59.9 dBm

The power level of the scattered return from the windmill indicated in Figure 5 is calculated next using Equation (10), as shown in Table 2.

Table 2: Calculation of scattered signal from windmill, L-band case.

$$P_{tower} = \frac{P_T G_T G_R \sigma_T \lambda^2}{(4\,\pi)^3\, d_1^2 d_2^2}$$

Parameter	Remarks	dB
P_T	Transmit power, 1 watt	30 dBm
G_T	Transmit gain, omni	0
G_R	Receive gain, omni	0
σ_T	Radar cross section of WTG	50
λ^2	f = 1200 MHz; λ = 0.25 m	-12
$(4\pi)^3$	Constant	33
d_1^2	Distance from Pad 7 to WTG = 1188 m	61.5
d_2^2	Distance from WTG to Pad 3 = 564 m	55.0
	P_{tower} =	-81.5 dBm

These calculations show that the signal reflected from the indicated tower would be well above the ambient background interference, and would compete strongly with the signal under investigation.

Typical UHF configuration

A recent experiment utilized transceiver to radiate 7 watts through an antenna which has 2 dB gain. The signal was received at the receive site through a discone antenna, which is essentially omnidirectional.

The desired and reflected signal levels can be computed using (5) and (10) as before. Table 3 shows the parameters for the representative configuration, and the calculated received power level of the desired signal. The received signal level is calculated to be -34.9 dBsm.

Table 3: Representative configuration parameters and calculation of desired signal level, UHF case

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\,\pi)^2\, R^2}$$

Parameter	Remarks	dB
P_T	transmit power, 7 watts	38.5 dBm
G_T	Transmit gain, omni	2
G_R	Receive gain, omni	0
λ^2	f = 225 MHz; λ = 1.33 m	2.5
$(4\pi)^2$	Constant	22
R^2	Range = 624 m	55.9
	P_R =	-34.9 dBm

The power level of the scattered return from the windmill is calculated next using Equation (10), as shown in Table 4.

Table 4: Calculation of scattered signal from windmill. UHF case.

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G_T	Transmit gain, omni	2
G_R	Receive gain, omni	0
σ_T	Radar cross section of WTG	50
λ^2	f = 225 MHz; λ = 1.33 m	2.5
$(4\pi)^3$	Constant	33
d_1^2	Distance from Pad 7 to WTG = 1188 m	61.5
d_2^2	Distance from WTG to Pad 3 = 564 m	55.0
	P_{tower} =	-56.5 dBm

These calculations again show that the signal reflected from the indicated tower would be well above the ambient background interference , and would also compete strongly with the signal under investigation.

8. Wind turbine generator siting requirements to reduce interference

Signals reflected from the proposed wind turbine generators will decay at a rate approximately $\frac{1}{D_T^4}$, where D_T is the distance of the wind turbine generator from the Stockbridge test facility. Scattered reflections from the proposed wind turbine generators can be made smaller than the existing ambient environment if the structures are placed far enough from the Stockbridge site.

Figure 6 shows the power of the reflected signal for the configuration of Table 2 (L-band, 1 watts, omnidirectional antennas) as the distance of the wind turbine generator from the receive site is varied. The power of the reflected signal decays exponentially with distance, and falls below the ambient background level at approximately 3,500 m. That is, wind turbine generators located more than approximately 2 nmi from the Stockbridge test facility would most likely have no significant effect on calibrated radio frequency measurements for this experimental configuration.

For the UHF configuration of Table 4 (UHF-band, 7 watts, 2 dB gain transmit antenna), the scattered signal level does not fall below the ambient background until 13,000 m, as shown in Figure 7. That is, wind turbine generators located more than approximately 7 nmi from the Stockbridge test facility will most likely have no significant effect on calibrated radio frequency measurements for this experimental configuration.

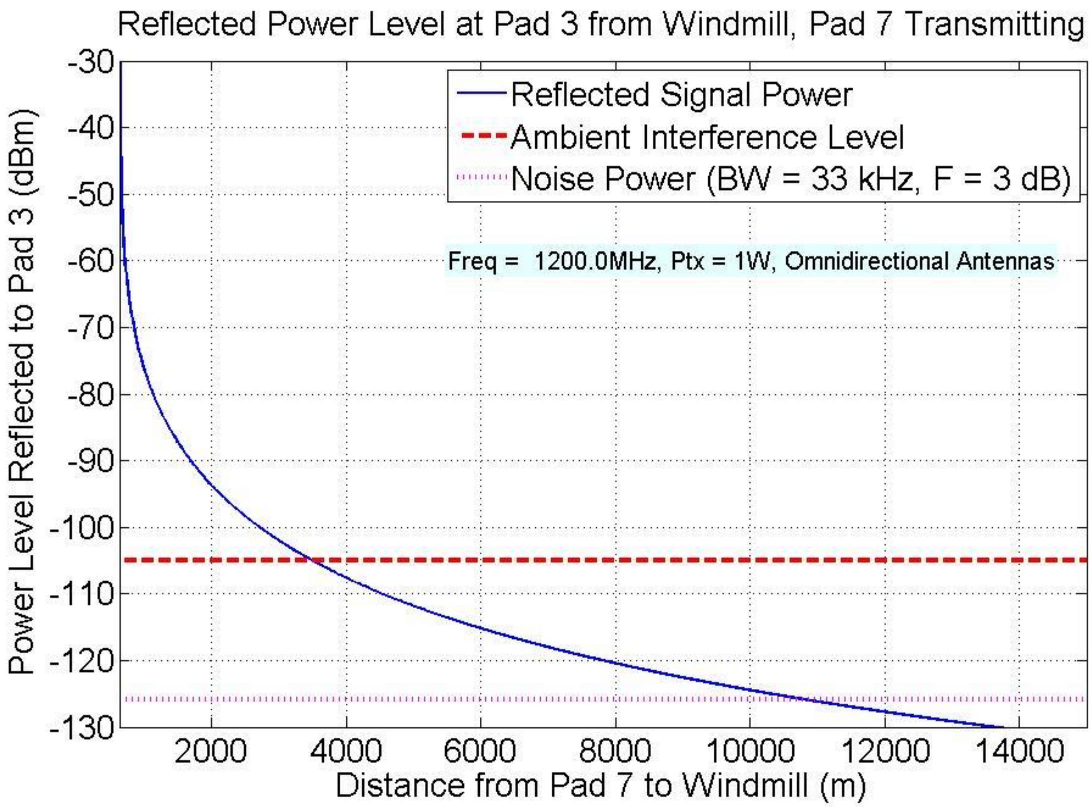

Figure 6: Scattered signal power level as a function of distance from receiver for low-power L-band case. Signals reflected from wind turbine generators will not have significant effect on the representative configuration if structures are located 2 nmi from the site.

Several other configurations were also examined, based on actual experiments performed at the Stockbridge facility within the past year. For each of these configurations, the distance of the wind turbine generator at which the scattered signal would fall below the ambient background is calculated. The results are summarized in Table 5. The results show that the proposed wind turbine generators within 3.5 nmi would most likely have impacted most tests performed at the site within the past year.

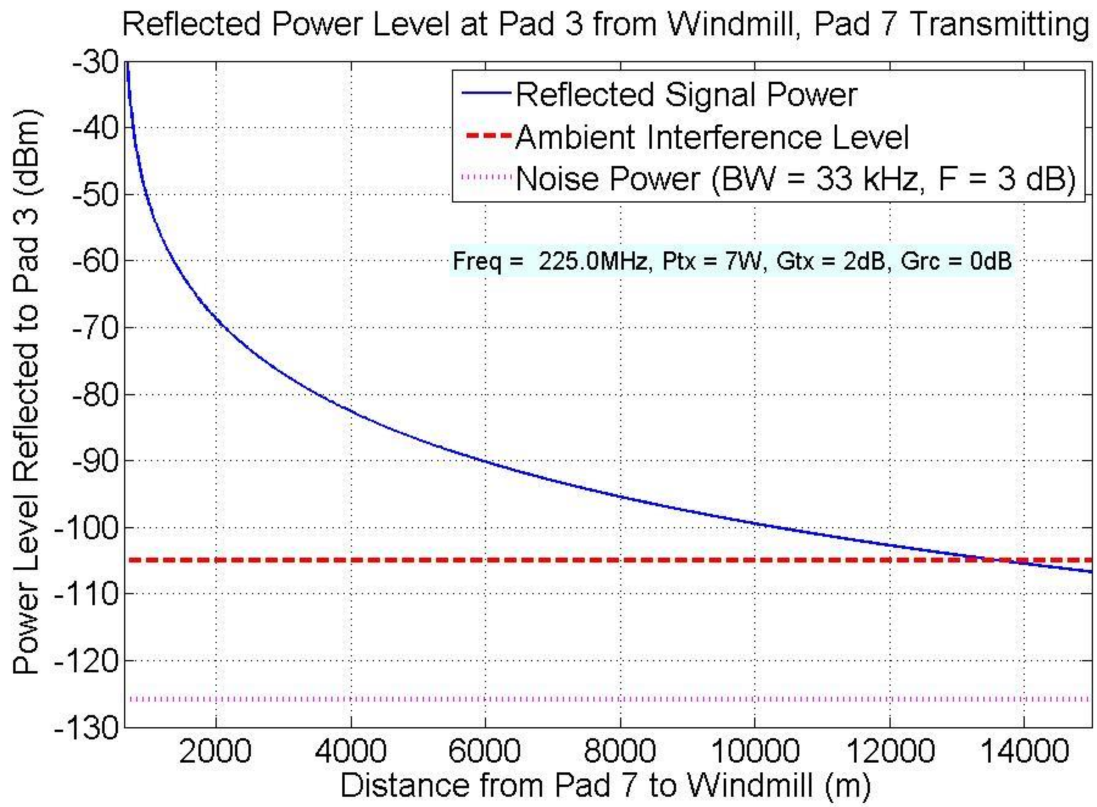

Figure 7: Scattered signal power level as a function of distance from receiver. Signals reflected from wind turbine generators will not have significant effect if structures are located 7 nmi from the site.

Table 5: Summary of separation distances required for recent experiment configurations

Frequency (MHz)	Transmit Power (W)	Transmit Antenna (dB)	Receive Antenna (dB)	Range of wind turbine at which scattered reflections fall below ambient background (meters)	(nmi)
225	7	2	0	13,000	7.0
296	1	0	0	6,500	3.5
364	2	0	0	7,000	3.8
427	2	0	0	6,500	3.5
435	1	0	0	5,500	3.0
918	1	0	0	4,000	2.2
1200	1	0	0	3,500	1.9
1800	100	0	0	8,000	4.3
2400	1	0	0	2,500	1.3
2400	0.1	13.5	0	3000	1.6
5200	0.04	6	0	1300	0.7

9. Summary

An analysis was performed of the power levels of signals reflected from wind turbine generators, and their potential impact on calibrated radio frequency measurements. The results indicate that wind turbine generators of the size proposed under the planned project located more than 7 nmi from the Stockbridge test facility will most likely have no significant effect on calibrated radio frequency measurements performed at the site. Structures placed between 3.5 nmi and 7 nmi would most likely impact higher power experiments in the upper frequency ranges, as well as moderate power experiments in the lower frequency bands. Structures placed within 3.5 nmi would most likely have impacted most tests conducted at the site within the past year. Wind turbine generators located 1 nmi from the site would most likely not interfere with only the lowest power experiments, namely those utilizing commercial wifi devices in the 5200 MHz band (IEEE 802.11b).

This analysis considered only scattering, and did not include other potential sources of interference, such as Doppler effects imparted from rotating blades, and electromagnetic fields produced from multi-Megawatt generators and their associated transmission lines. These effects should also be studied.

10. References

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