

**Executive Report II**

**Version 2.0**

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**Comprehensive Modeling Analysis for  
Stand-Off Requirements of Wind Turbines from  
Relocatable Over The Horizon Radar (ROTHR) Systems**

June 2012

ROTHR Program Office

## Foreword

For over 30 years, High Frequency (HF) Over-The-Horizon (OTH) radars have played vital roles in meeting national security surveillance requirements, initially to protect against Soviet bomber attack during the cold war. Currently they are used to detect and monitor drug-smuggling flights from Central and South America into the United States, and potentially in the future to provide surveillance beyond the nation's borders in the homeland defense mission. The OTH radar community is very concerned about the impact of adjacent wind farms on the radars' ability to continue to perform in these roles.

Current generation wind turbines are extremely large, radio-wave-reflecting structures. The turbine blade span can exceed the wingspan of a 747 jumbo jet, and the turbine tower heights are equivalent to a 40-story office building. The blades rotate every few seconds so the reflected radio waves are Doppler shifted up to a couple of hundred knots by the velocity of the blade surfaces. OTH radars detect moving targets against a background of backscatter from the earth's surface, or clutter, by virtue of the speed-induced Doppler separation between their reflections and those of the stationary clutter. However, the secondary reflection of those clutter signals off nearby turbines introduce a spectral contamination to the clutter backscatter which spreads it into target Dopplers. This creates a background against which target returns must now compete, and the radars' ability to detect targets is reduced, in much the same way that municipal light pollution of the night sky prevents astronomers' ability to see stars.

As with the night sky light pollution, the problem will be less pronounced as the separation between the interfering wind farm and the radar increases. Consequently, the ROTH Program Office has undertaken a study to determine the minimum wind farm stand-off distance from an HF radar site. This stand-off distance is required to guarantee that this "pollution" will not degrade the performance of the radar in its surveillance roles.

The study has proceeded along two complementary paths, using fundamentally different approaches. The first approach originated as a quick effort to identify the characteristics and level of the interference, and was based on empirical measurements of HF radar scattering from operational wind turbines [Reference 1]. Results were documented in the first Executive Report released in October 2011 [Reference 2]. The second approach, which is the subject of this report, develops a rigorous analytical formulation of the problem that entails modeling the electromagnetic interactions of turbine structures and antennas via the space and ground waves. Although the two approaches are mutually consistent in many ways (for example, the interference modulation signatures expected based on analytic modeling were confirmed via the measurements), the comprehensive modeling of the second approach has resulted in significantly increased wind farm stand-off requirements.

The first approach proceeded within the practical limitations of the empirical measurements and utilized a number of assumptions. For example, the turbine scattering measurements utilized transmitters and receivers that were sometimes only a few hundred meters from the turbine. In addition, during the measurements the turbines faced primarily one direction. An estimate of required stand-off distance was made from a "radar range-equation" formulation, in which the electromagnetic scattering by the

rotating wind turbine blades was described in terms of an equivalent radar cross-section (RCS). Estimates of RCS values were derived from the limited near-field experimental measurements. These values were then assumed to be relevant to the somewhat different skywave geometry. This is not totally correct but approximations had to be utilized for the empirical approach while the comprehensive modeling was ongoing.

The analytic approach reported here models the spectral contamination of the radar signal by the turbine scatter, and formally accounts for the interaction between antennas and turbines using rigorous models. These models take into account the scattering interaction of the turbine blades with the nacelle and tower and with the non-uniform fields near the earth's surface associated with the space and ground waves. It also allows for a more complete description of these interactions in operationally-relevant geometries with fewer extrapolations necessary to arrive at a bottom-line system impact and standoff distance. The analytic approach affords greater control over the range of parameters characterizing the radar/turbine interactions (for example, variation of the orientation of the turbine spin axis as wind direction changes, which allows evaluation of interference levels at all orientations).

Using comparable starting parameters and interference criteria, these two approaches produce standoff distance requirements reasonably consistent for similar turbine tower/blade/hub/nacelle structures, but are also highly sensitive to the nacelle orientation and the amount of attenuation of the turbine-scattered signals occurring between the wind farm and the radar. The recommendations shown in this report are based on the rigorous analytical approach and apply to average, smooth ground without obstructing terrain, vegetation, or buildings, all of which could reduce the scattered field strength reaching the radar thereby reducing the required standoff distance. Similarly, any constraint restricting turbine orientations to less interfering alignments (such as a naturally occurring prevailing wind direction or artificially-imposed limitations to the turbine spin axis orientation) could also reduce the standoff requirements. Any critical scenario should be subject to more detailed modeling of the propagation path and wind direction.

## Executive Summary

This report summarizes predictions of interference to Over-the-Horizon (OTH) radars from nearby wind turbine generators. The predictions are based on the rigorous application of Numerical Electromagnetic Code (NEC) modeling to characterize the electromagnetic interactions occurring via low elevation propagation mechanisms between single rotating wind turbines and OTH radar antennas. These predictions are then extended to determine the degradation to operational OTH radars caused by interference from distributed wind turbines in farms of tens to hundreds of units. The results are summarized in recommended stand-off distances from OTH radar transmit and receive arrays from generic wind farms of various sizes: single turbine, small (25 turbines), and large (165 turbines). The standoff distances apply anywhere within the azimuth sector scanned by the OTH radar, and the complementary sector 180 degrees behind it. The recommended standoff distances based on the analysis reported here are:

	Transmit		Receive	
	Front	Behind	Front	Behind
Single Turbine	15 km	5 km	25 km	10 km
Small Farm	35 km	10 km	40 km	15 km
Large Farm	45 km	15 km	45 km	15 km

At these standoff distances, it is predicted that the highest level of interference for a target radial speed of 50 knots or greater will be no more than -76 dB relative to the surface clutter at any radar operating frequency (5 to 28 MHz). These recommended standoff distances are considerably greater than the previous preliminary analysis (Reference [1]) in which a standoff distance of 15 km was determined for a 10-turbine farm, producing an interference level of -70 dB at an unspecified target velocity. The last section of this report predicts the interference levels on the Virginia and Texas ROTH systems from three planned wind farm projects lying closer to the ROTH sites than the tabulated standoff distances. These wind farms consist of 23, 29, and 158 turbines. The interference from these planned farms is shown to be severe, compromising the ability of these radars to detect and track targets with speeds as high as 150 to 200 knots. The latest proposal for the significant expansion of the Hales Lake wind farm is not addressed in this report due to time constraints.

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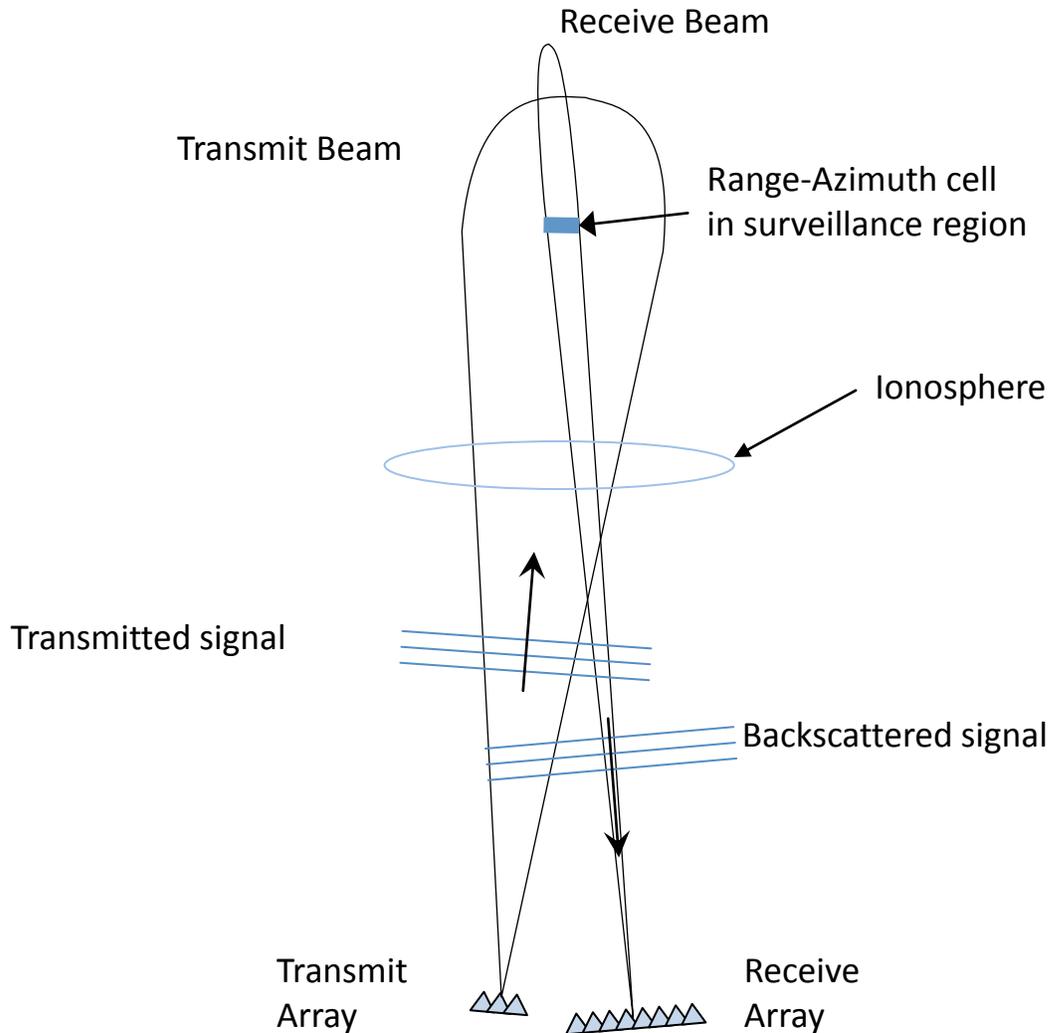
Table 4. Minimum Standoff Distances from Transmit and Receive Arrays

## 1 Introduction

In order to appreciate the concern the OTH radar community has for the effects of nearby wind farms on OTH radar performance it is useful to consider the typical OTH radar system geometry depicted in Figure 1. For OTH radars, transmit and receive functions occur at separate radar sites. These sites are separated by 50-100 miles and use independent linear transmit and receive arrays that produce beams confined in azimuth, but, with very little directivity in elevation. The transmit site radiates a coherent pulse-Doppler waveform in the direction of a desired surveillance region, typically a few thousand km away, which is reached by propagation through a refracting ionosphere. The signals arriving downrange are scattered off targets in the surveillance region and also off the ground or ocean. The portion of the scattered energy going back toward the receive array is signal processed on reception in range and azimuth. This processing isolates scatter received from small down range regions in range and azimuth (range-azimuth cell), the size of which is determined by the bandwidth of the radiated waveform and the beamwidth of the receive array. Because the receive array is several times the length of the transmit array, the azimuth beamwidth of the range-azimuth cell is several times smaller than the transmit beamwidth. Therefore, multiple receive beams are typically formed to extend the processed surveillance region over the width of the transmit beam.

Because the clutter backscatter is many orders of magnitude larger than the backscatter from targets of interest, targets can only be detected if they possess a velocity component radial to the radar. The Doppler-shifted targets are separated from the zero Doppler clutter by coherent pulse-Doppler processing of the received backscatter, forming a bank of Doppler filters or bins. The success of this separation depends on achieving minimal leakage of the surface clutter backscatter into the target Doppler cells. Minimal leakage requires transmission of very pure spectral signals, and reception of very pure spectral clutter backscatter. There are many factors that limit the purity of the transmitted signals and backscattered clutter, but in normal operating conditions, which can be extremely variable (e.g. sunspot, seasonal, and diurnal variations in the ionosphere), environmental stabilities can be relied upon to allow sub-clutter visibility (SCV) of more than 70 dB below the clutter level in non-zero Doppler bins. In current generation OTH Radars, 70 dB SCV is typically achieved and therefore, this report will reference interference as 1 dB of clutter contamination above 70 dB SCV.

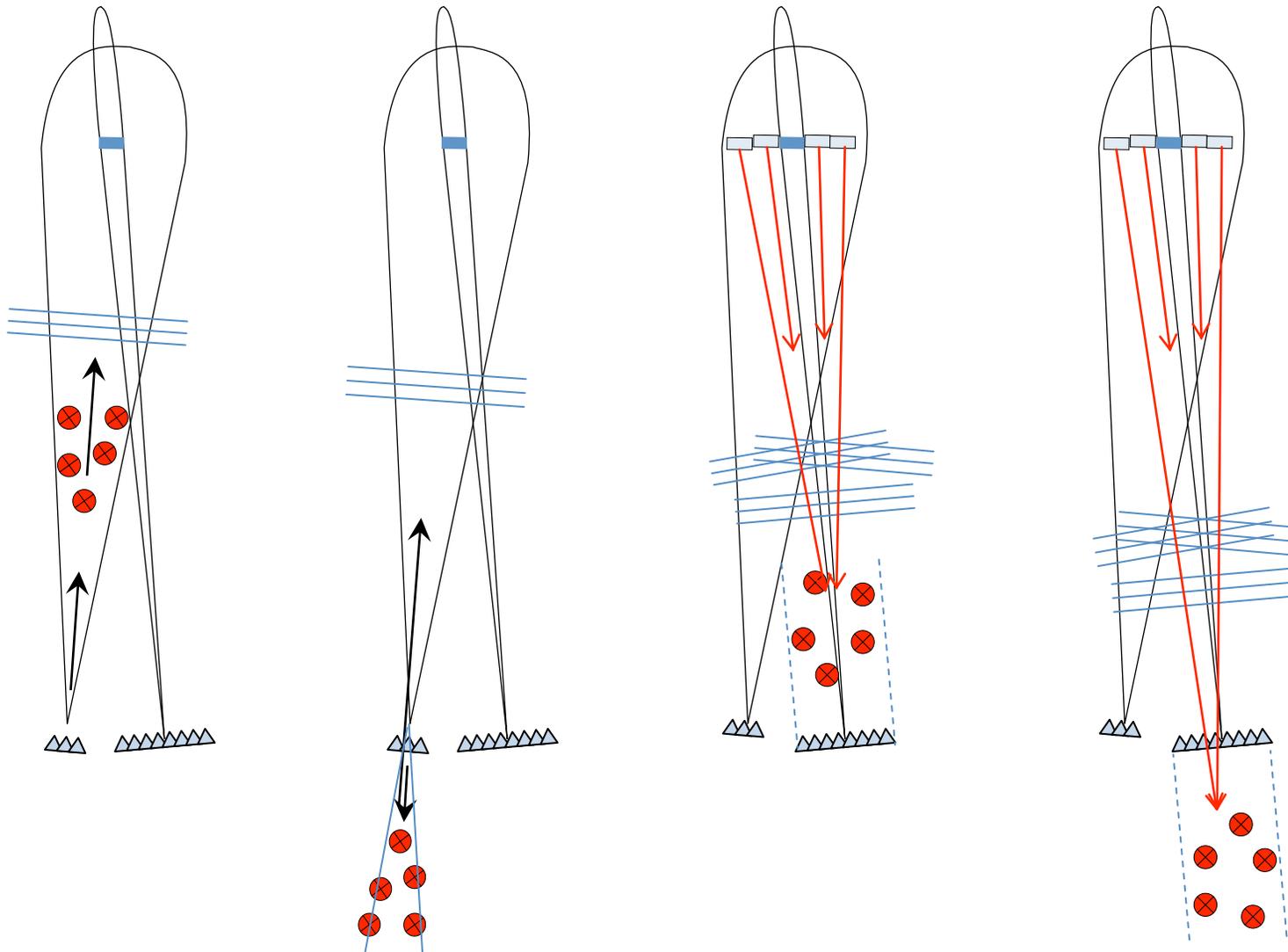
The threat posed to OTH radar performance by wind turbines and particularly wind farms near the OTH sites is that on transmit, a portion of the transmitted signal will be scattered off the moving blades of the wind turbines. In the process these signals are modulated in amplitude and phase to produce a spectral spreading in the turbine-scattered signal. The scattered and spread signal then propagates downrange through the ionosphere along with the directly radiated signal so the total signal incident on the down-range clutter is the sum of the original signal and the spectrally-contaminated wind farm scatter signal. This composite signal produces a degree of spectral broadening on the backscattered surface clutter, and hence higher leakage into target Doppler cells.



**Figure 1.** OTH Radar Geometry (plan view)

The corollary threat on the receive side is that a portion of the surface backscatter reaching the receive array vicinity is incident on the wind farm turbines and modulated and scattered toward the receive array. When added to the surface backscatter arriving via the direct path, the composite surface backscatter possesses a degree of spectral broadening which creates higher clutter leakage into target Doppler bins.

The transmit and receive site cases are illustrated in Figure 2 (a) and (b). In each case, the wind farms may be positioned in front of the arrays, producing forward scatter off the turbines, or behind the arrays producing backscatter from the turbines. All four cases have been addressed in this analysis. Generally, turbines positioned in front of the arrays are a larger problem because the front-to-back ratios of the antenna patterns will reduce the scatter from turbines behind the arrays relative to the direct path clutter and targets from in front of the arrays.



(a) Wind farm near transmit array

(b) Wind farm near receive array

Figure 2. Wind farms Near OTH Radars

## **2 Analysis of the Receive Path Problem**

The most significant level of interference is the receive problem shown in Figure 2(b) and will be discussed to detail the analysis process. The concern is for the spectral contamination produced by a farm of wind turbines located near and in front of the receive array. In the absence of the wind turbines the surface clutter backscatter processed by the radar is from within the rectangular patch bounded by the receive beam and range bin. When the turbines are inserted, the identical backscattered signal is incident on the turbines, and a portion is scattered toward the radar, reaching it by a geometry-dependent combination of ground wave and line-of-sight propagation. The scatter is modulated in amplitude and phase by the motion of the turbine blades and the total surface clutter backscatter at the receive array is the sum of the direct and turbine-scattered signals. In order to analyze the effect of the turbine scattered signal it is desired to produce the spectrum of the total surface backscatter from both paths combined and seen at the output of the receive range, beam, and Doppler processing.

Figure 3 (a) to (d) illustrates the sequence of modeling steps to predict the receive path interference levels. The four steps are:

- a. Single far-field source, single turbine, single receive element interaction
- b. Single far-field source, single turbine, full receive array
- c. Distributed far-field source, single turbine, full receive array
- d. Distributed far-field source, distributed turbines (wind farm), full receive array

### **2.1 Receive Path Modeling Step (a). Single Far-field Source, Single Turbine, Single Receive Element**

The first step in the analysis models the interaction between a single turbine and a single ROTHR receive antenna. The analysis determines the relative levels of the two arriving signals as seen at the output terminals of the antenna. The first signal is the direct arrival of a single frequency signal originating from a point source in the far field. The second is the signal scattered from a turbine at a reference range from the receive antenna, when illuminated by this same far-field source. A spectral description of the turbine scatter interference is obtained by calculation of the ratio of the two signals at each of 64 turbine blade positions, uniformly-spaced over 120 degrees of turbine rotation, which constitutes one period of the periodically repeating modulation for a three-bladed turbine. The main features of the turbine model utilized for this task are summarized below:

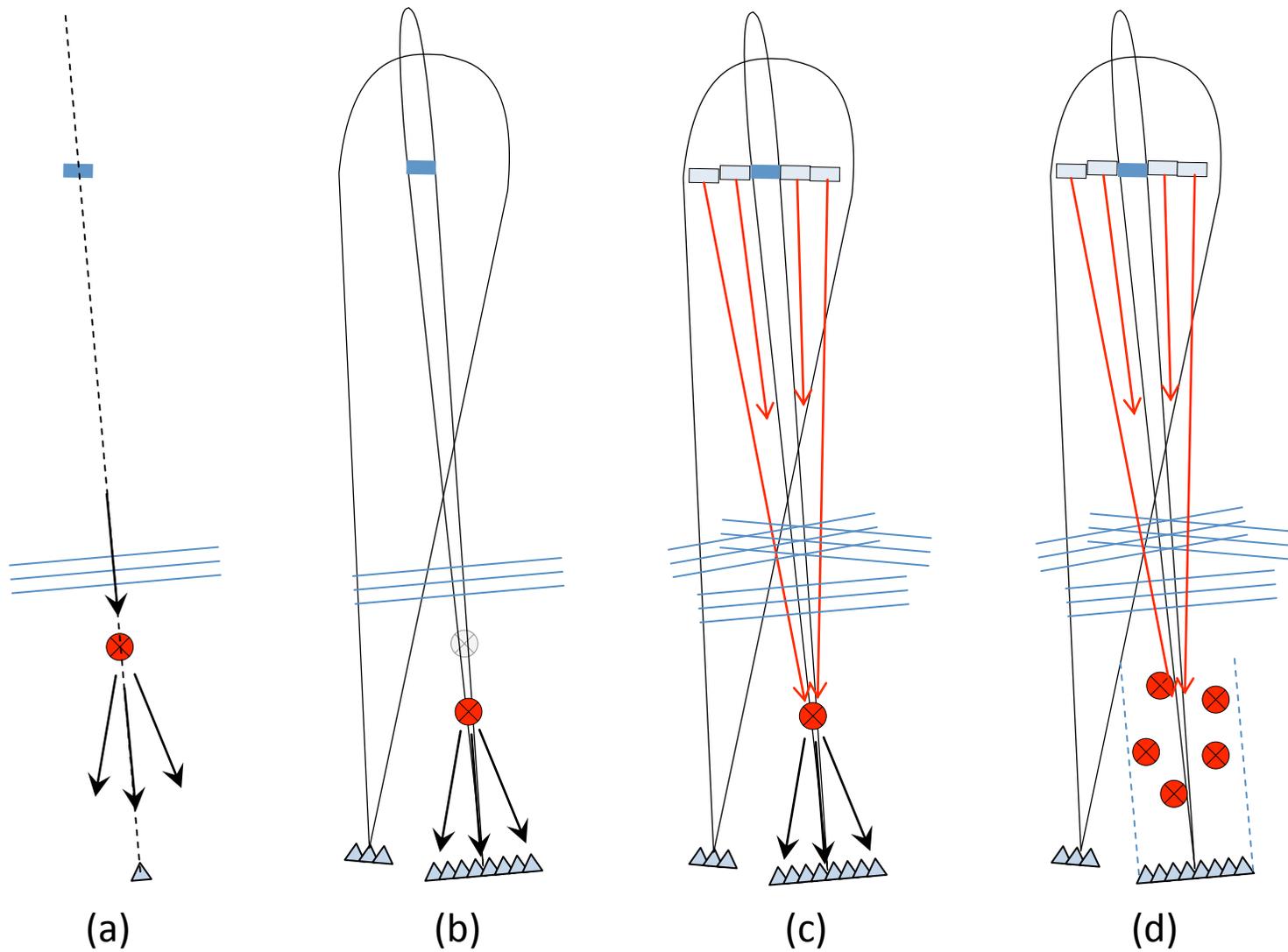


Figure 3. Receive Path Wind Farm Interference Modeling Steps

**Table 1.** Turbine Model Features

Horizontal axis height	96.76 m
Blade swept diameter	100 m
Blade conductor (lightning wire)	10 mm diameter
Tower cross section	dodecagonal
Tower diameters:	
Base	4 m
Top	3 m
Tower material	all-metal
Foundation rods	12x20mx6" dia
Nacelle	6mx3mx3m
Hub diameter	3m, plus extensions

All subsequent modeling steps, including scattered signal level adjustment for variable turbine-to-antenna distance, beamforming and focusing loss adjustment for combining all receive antenna elements in the array, summation of signals arising from all transmit-illuminated far-field scatterers, and summation of signals from multiple turbines comprising the wind farm, are based on this single element, single turbine interaction analysis. Details for this fundamental modeling are provided in a separate report, Wind Turbine RF Wave Scattering at HF Frequencies: Doppler Analysis of the Relocatable Over The Horizon Radar (ROTHR) [Reference 3]. The report addresses the complete turbine scattering and modulation processes for a single turbine. It evaluates the signals arriving at the receive antenna and those propagating toward the far field when the turbine is excited by the transmit antenna. It also evaluates the signals coupled into the receive antenna and propagating back toward the far field when the turbine is excited by signals arriving from the far field. These evaluations produce the kernels of the transmit and receive scattering models which describe the interactions between a single turbine, a single element of the ROTHR receive array, and the high and low band ROTHR transmit arrays.

The basic approach followed in the Reference [3] report relied on the application of Numerical Electromagnetics Code (NEC) [Reference 4]. In the early development of the NEC turbine model, a validation effort was conducted to ensure that results were consistent with empirical measurements of scattering from operational wind turbines collected and reported in Reference [2]. This effort is detailed in the separate report, NEC Turbine Model Validation, Ver. 1.0, and [Reference 5]. The results showed very good consistency of scatter response at various frequencies between the NEC model and the measured data. This validation and subsequent refinements of the NEC model provided for certain modifications essential to overcome its drawbacks: (a) only deals with perfectly flat, homogeneous ground, and (b) to accurately account for the interaction of the turbines with the transmit and receive arrays and their ground screens, extremely large NEC segment counts would be necessary.

For this evaluation, the first drawback can be ignored. The fields near the ground (within turbine heights) were evaluated with NEC and with GRWAVE [Reference 6] at 25 Km for sources at typical turbine and antenna heights, and found to be nearly identical. This result was expected because the formulations used by NEC and GRWAVE in the region below the critical distance are basically the same. For distances beyond 25 km, where diffraction due to earth curvature begins to become relevant, the fields predicted at 25 km were extrapolated using GRWAVE basic transmission loss differences.

Evaluation of the 2<sup>nd</sup> drawback produced methods to actually use NEC to configure approximate simple models of the transmit and receive antennas and their ground screens. These simpler models proved valid for ground wave and sky wave calculations (low elevation angles) using current-moment sources (transmit) and vertical apertures (receive). An added advantage of the current-moment based models is they directly provide turbine scattering contributions without the need for NEC modifications to compensate for the limited accuracy of its standard outputs. The drawing in Figure 4 illustrates the EZNEC turbine model, including current flow at 5 MHz.



**Figure 4.** EZNEC Turbine Model, Showing Current Flow at 5 MHz

Having the model elements developed, the analysis concentrated on the evaluation of the spectral contamination of the radar signal by the turbines and formally accounting for the interaction between

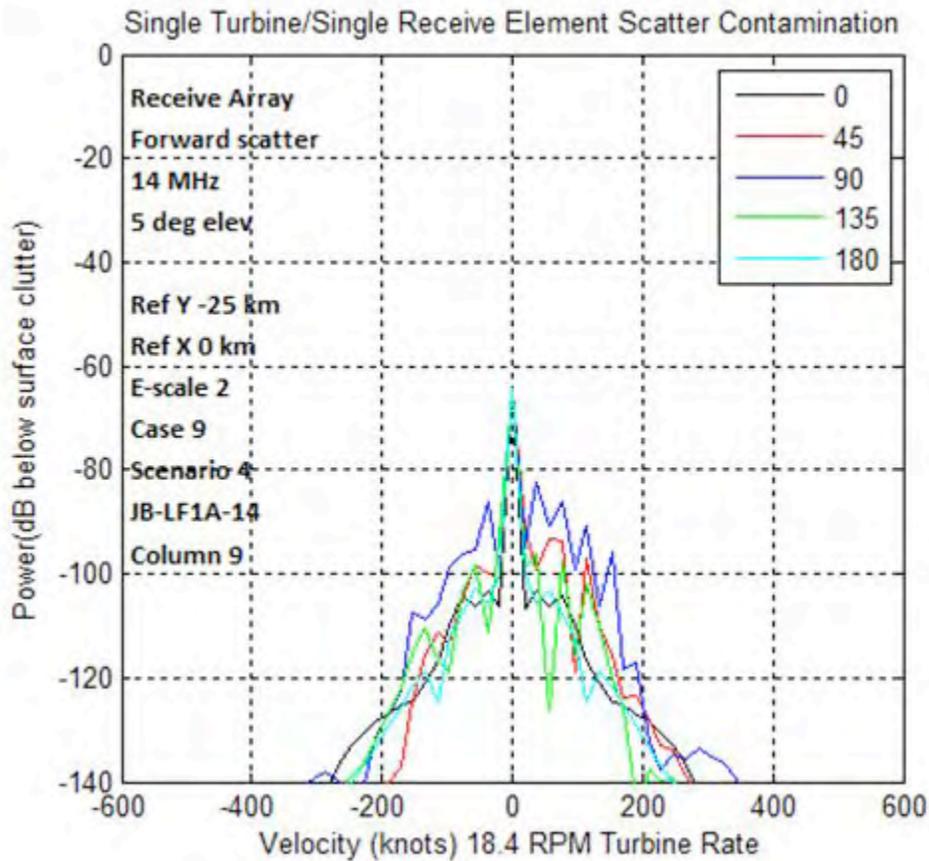
antennas and turbines. Rigorous models were used to account for the interaction of the turbine blades with the nacelle and tower and for the interaction of both turbine structures and antennas with the non-uniform fields near the surface associated with the space and ground waves.

The analysis assumed a stationary interaction process over smooth, homogeneous, average terrain. As such, it assumed a number of propagation-related factors can in principle be considered to average out, such as,

- a. non-uniformity of the ground electrical parameters along the propagation path,
- b. terrain features such as hills, and vegetation of different kinds,
- c. propagation over urban areas
- d. seasonal and meteorological related effects,
- e. night/day and frequency dependent fading due to ionospheric wave interference.

The modeling was carried out at three frequencies, 5, 14, and 24 MHz, and for 5 turbine rotational axis positions relative to the plane of modeling. The modeling and analysis methodology extending the single turbine, single antenna results are illustrated below at 14 MHz for forward scatter geometry (applicable when the wind farm is in front of the ROTHr receive array). Results at other frequencies and backscatter geometry (wind farm behind ROTHr receive array) are presented later in tabular form in Table 2.

Figure 5 illustrates the normalized interference spectrum produced for 5 degrees arrival elevation, for forward scatter at 14 MHz, from a single turbine positioned 25 km in front of the receive antenna. Five spectra are plotted, each presented in dB below the normalized direct arrival signal. The 5 plot lines represent each of 5 turbine/nacelle/blade assembly positions spaced at 45° increments rotated from 0° to 180° (0° represents the turbine spin axis pointing toward the ROTHr array, 180° pointing away from the array, and 90° pointing perpendicular to the great circle between the array and the turbine). The spectrum of the normalizing direct path signal is not shown but consists of a single spectrum line at 0 Doppler, power level 0 dB. The scatter modulation spectral lines are positioned on the assumption of an 18.4 RPM turbine rotational speed. For example, at the Doppler shift of a +200 knot radial speed target, the turbine scatter would be at a level of -120 dB relative to zero-Doppler clutter. This case is for a single rotating turbine with a rotational axis positioned at 90 degree. That level is well below the -70 dB level of the typical background noise environment. However, at lower target speeds the turbine contamination is more significant. At around +50 knots, the turbine contamination level is seen to be about -82 dB relative to the zero-Doppler. While this appears not to be large enough to raise the total background level significantly, it will become more predominant when the far field source becomes a distributed source and received by an array of antenna elements. The cumulative interference effect can then be shown to become large enough to interfere with both target detection and tracking for OTH radars.

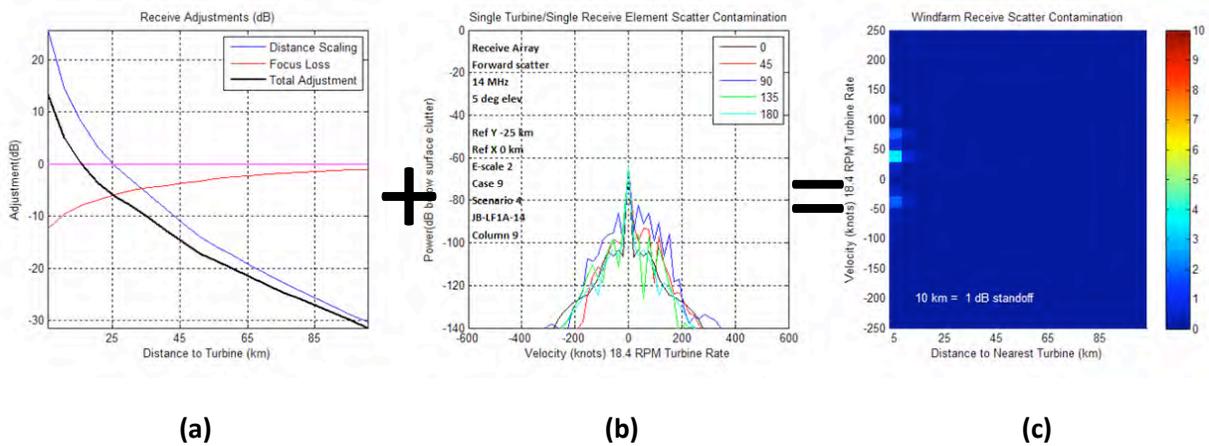


**Figure 5.** Single Source, Single Turbine, Single Receive Element Scatter Contamination  
14 MHz, 18.4 RPM, single-element receive array, turbine in front of receive array

**2.2 Receive Path Modeling Step (b).** Single far-field source, single turbine, full receive array

Continuing the 4-step interference path modeling scenario, step (b) in Figure 3 considers the results with multiple receive antenna elements. The OTH receive antenna is an array of the single element antennas modeled in step a. All elements of the array are combined together to form a steered directional beam, which is assumed in this analysis to be steered in the direction of the nearby wind farm. The beamforming step, illustrated in Figure 3(b), converts the single element result of step (a) to the receive array output. When forming a receive beam in the direction of the single far-field source, the analysis in this step predicts the level of spectral contamination produced by scatter from a single turbine path relative to the output signal level of the direct path. The conversion from the model in step (a) involves two factors: 1) a distance scaling to account for the actual distance of the turbine from the center element of the receive array relative to the 25 km distance previously modeled and 2) a focusing loss, relative to the array response to the direct path clutter, caused by the curvature in the phase-front of the near-field turbine scatter. Figure 6 (a) plots these two factors as a function of the distance of the

turbine from the receive array. The distance scaling accounts for the reduction in field strength in the region between the turbines and the radar antennas. For distances beyond 25 km, this reduction was calculated with GRWAVE at nominal heights of 10 m and 150 m respectively at each end of the propagation path. At smaller distances the fields were extrapolated using a power law of  $D^2$  for 5 and 14 MHz, and  $D^{1.95}$  for 24 MHz. The scattered power decays as the magnitude squared E-field. The focus loss calculation includes the effects of the phase and amplitude deviation from constant amplitude, planar wavefront due to the unequal distances from the turbine to elements in the array. The modeling in step (a) used a source, turbine, and receive element that were coplanar in elevation. Extending this to the full receive array, it is assumed the forward scatter from the turbine is isotropic over the angle subtended at the turbine by the receive array. For a ROTH 372-element receive array, this angle varies from +/- 7 degrees at 10 km to +/- 1/2 degree at 180 km.

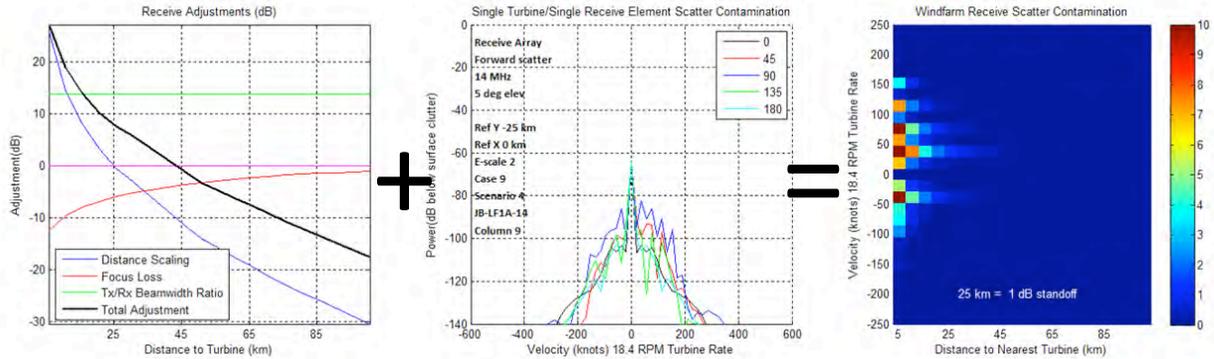


**Figure 6.** Single Source, Single Turbine, Multiple Receive Element Contamination  
 14 MHz, 18.4 RPM, 372-element receive array, turbine in front of receive array

Figure 6 (c) combines the scaling and spectrum of 6 (a) and (b) and plots the degradation to SCV for the worst case turbine orientation; on the convention that 70 dB SCV is achieved in the absence of the turbine scatter. 1 dB of SCV degradation results when the level of turbine scatter is about 6 dB below the ambient background level, which occurs at a distance of about 10 km in this instance. The level of turbine scatter is about 82 dB below the ambient background level at a distance of 25 km in step(a). At a distance of 10 km from the receive array, the interference power from a single turbine increases by +15 dB relative to the power at 25 km, but with the focusing loss of about -9 dB from the array, there is a net scatter reduction of about 6 dB relative to a single receive element. This produces an array output scatter level at 50 knots of -76dB, and consequently a 1 dB degradation of the ambient -70 dB SCV.

### 2.3 Receive Path Modeling Step (c). Distributed far-field source, single turbine, full receive array

The far-field source providing the incident signal being scattered by the turbine in step b is the surface clutter contained within the single range-azimuth cell producing the direct-path return. Because the transmit beam is many times wider than the receive beam, it is illuminating more than one such range-azimuth cell in each given range cell, as illustrated in Figure 3(c). The direct path surface scatter from these additional azimuth cells is rejected by the receive beam sidelobes, but the additional energy is incident on the wind turbine and scattered with the same phase front curvature as the scatter from the cell on beam center. Consequently, the total power incident on the turbine, and scattered toward the receive array, is many times larger than has been calculated so far. The average increase in scattered power is equal to the ratio of the transmit and receive beamwidths, which for ROTH is about 11 dB for the low band transmit array (used below 11 MHz) and about 14 dB for the high band transmit array (used above 11 MHz). Figure 7 plots the single turbine scatter contamination when this factor is accounted for.



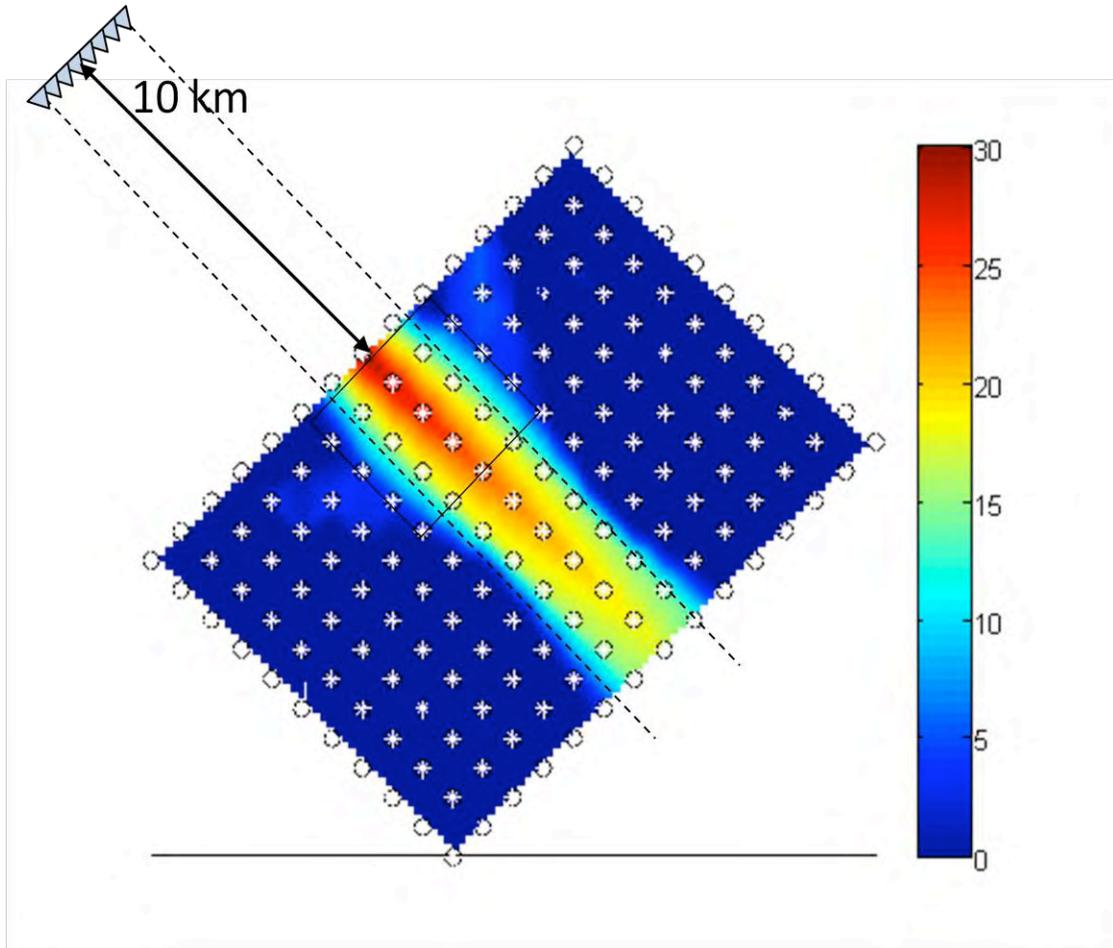
**Figure 7.** Distributed Far-field Source, Single Turbine, Multiple Receive Element Contamination  
14 MHz, 18.4 RPM, 372-element receive array, turbine in front of receive array

As this figure shows, the turbine interference level at 50 knots radial speed is considerably greater than that considered from a single range-azimuth cell. By this example, the need for an additional 14 dB of reduction to the scatter levels incident at the receive array increases the required standoff distance from 10 km to 25 km. This factor is added to the combination of terms in receive path modeling and leads to step (d) finally accounting for multiple turbines within effective range of the OTHR receive array.

### 2.4 Receive Path Modeling Step (d). Distributed far-field source, distributed turbines (wind farm), full receive array

The final step, illustrated in Figure 3(d), expands the single turbine result of step c to farms of multiple wind turbines. The total scatter contamination from the farm is the sum of contributions from all turbines in a wind farm scenario, each scaled for individually calculated distance adjustments and focus losses. Figure 8 illustrates the relative power responses of an 11x15 field of turbines at 1 km spacing,

starting at 10 km from the receive array, at 14 MHz. A smaller 5x5 field is indicated by the box in Figure 8. Color represents the relative power contribution to the sum, in dB, of each turbine. Note the collimated, non-diverging receive beam shape. This is due to the location of the wind farm within the near-field region of the large receive array. The receive beam does not begin to effectively spread until a far field distance of  $2D^2/\text{wavelength}$  is reached.

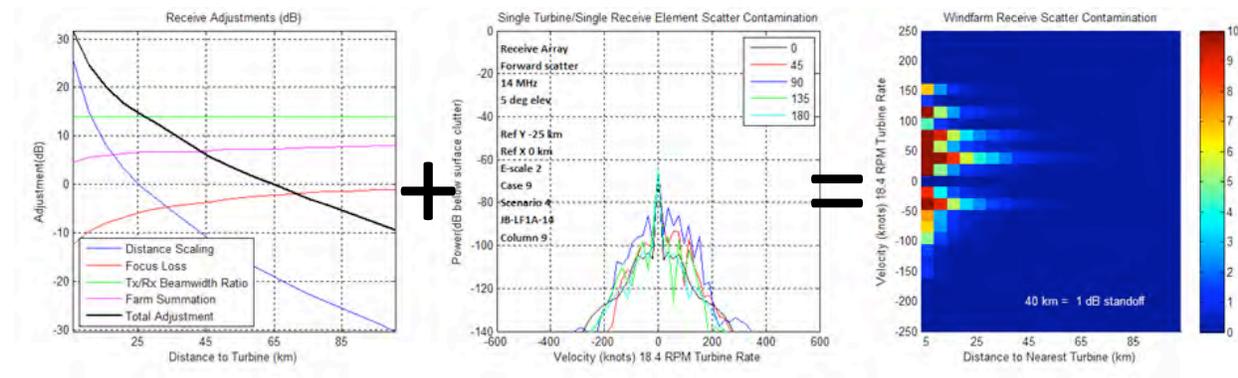


**Figure 8.** Relative Turbine Scatter Receive Array Responses  
14 MHz, turbines in front of array, at 1 km spacing, 10 km from array

The average power in the sum of the scatter from the turbines in the farm is equal to the sum of the powers from each individual turbine weighted by the relative responses shown in Figure 8. The result of this summation produces a multiplicative farm summation term describing the increase of the interference over the single turbine case. This farm summation term is upper-bounded by the number of turbines within the response region of the receive array. The width of this region depends on the range from the array. In the near field of the receive array (out to about 80 km at 14 MHz), the width is approximately the effective length of the amplitude-weighted array, or about 1.3 km. In the far-field region (beyond 80 km at 14 MHz), the width equals the azimuth beamwidth. At 10 km, the 5x5 farm is

within the near-field region of the array, and the effective number of turbines contributing to the farm summation term is about 7, resulting in a farm summation factor of about 8 dB. This is valid out to the 80 km transition from near to far-field, and then growing proportional to range thereafter to an asymptotic value equal to the number of turbines. For the small 5x5 field of turbines shown, this asymptotic value of 25 (14 dB) is not reached until a distance of about 300 km, the range at which the far-field receive beam contains the full width of the 5x5 farm.

Figure 9 illustrates the final contamination result for a hypothetical wind farm of 25 turbines, arranged in 5 rows of 5 elements, spaced at 1 km intervals. In this example, the need for an additional 8 dB of reduction to the scatter levels incident at the receive array increases the required standoff distance from 25 km to 40 km.

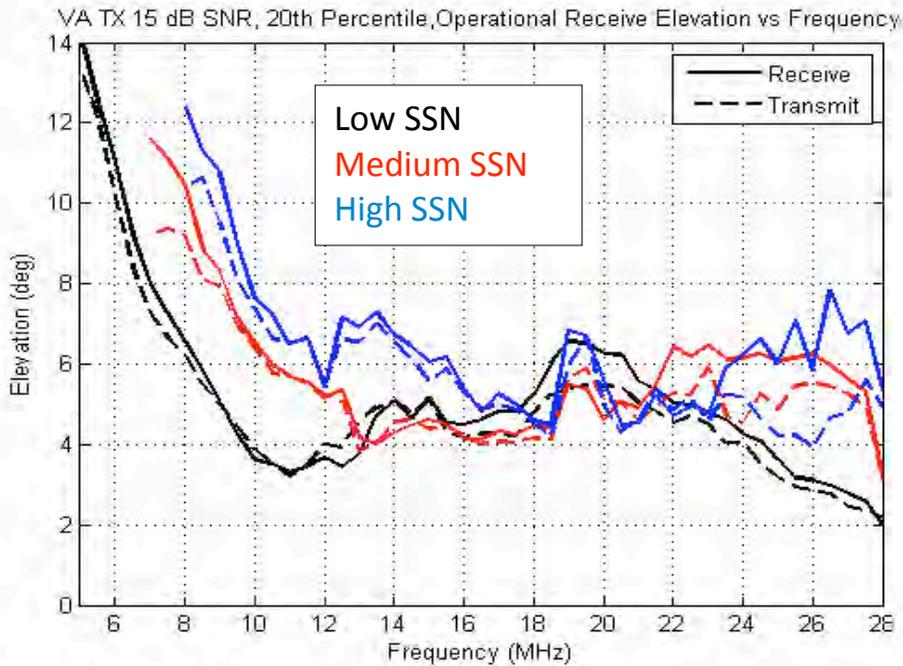


**Figure 9.** Distributed Far-field Source, Multiple Receive Element, Distributed Wind farm Contamination 14 MHz, 18.4 RPM, 372-element receive array, turbine in front of receive array, 5x5 turbines at 1 km spacing

### 3 Receive Standoff Distance Requirements

The calculations described in Section 2 above were carried out for three frequencies of 5, 14, and 24 MHz, for a single turbine, a small 25 turbine wind farm, and a large 165 turbine wind farm to determine a recommended standoff distance from a ROTHr receive array.

Standoff distances were determined for wind farm turbines in front of the array, behind the array, and for operationally relevant arrival elevations. The results are summarized for frequency, elevation, and wind farm size in Table 2 below. Operationally relevant elevations were determined by modeling Virginia and Texas ROTHr operations, to obtain the distribution of arrival and departure elevation angles of incident far-field target and surface clutter signals vs. frequency of operation. The results of this analysis, plotted in Figure 10, shows the 20<sup>th</sup> percentile elevations (20% are lower) vs frequency.



**Figure 10.** 20<sup>th</sup> Percentile Arrival Elevation vs. Frequency and Sunspot Number, Virginia and Texas ROTH

Although initial predictions of turbine scatter levels were calculated for a fixed 5 degree elevation, based on the results shown in Figure 10, those at 5 MHz were extrapolated to 18 degrees, so that all scatter predictions would apply to the 20<sup>th</sup> percentile elevation. Higher target elevations will produce lower relative levels of interference from wind farms located near the OTHR arrays. This is because the antenna gains are larger at the higher elevation angles relative to the contaminated signal loss over the array-turbine path. In addition, the scattering levels from the turbines will decrease as the incident or departure angles increase. For example, at 5 MHz, 18 degree incident elevation, the forward and backward turbine scatter is estimated to be approximately 2 dB lower than for 5-degree incidence. In addition, the ROTH receive element response at 5 MHz, 18 degrees is about 4 dB higher than at 5 degrees (providing a net rejection to the turbine scatter signal) for a net decrease in the relative scatter spectrum contamination level to 6 dB. A similar extrapolation was made for the transmit case. This adjustment for elevation incidence provides the standoff requirements tabulated in Table 2.

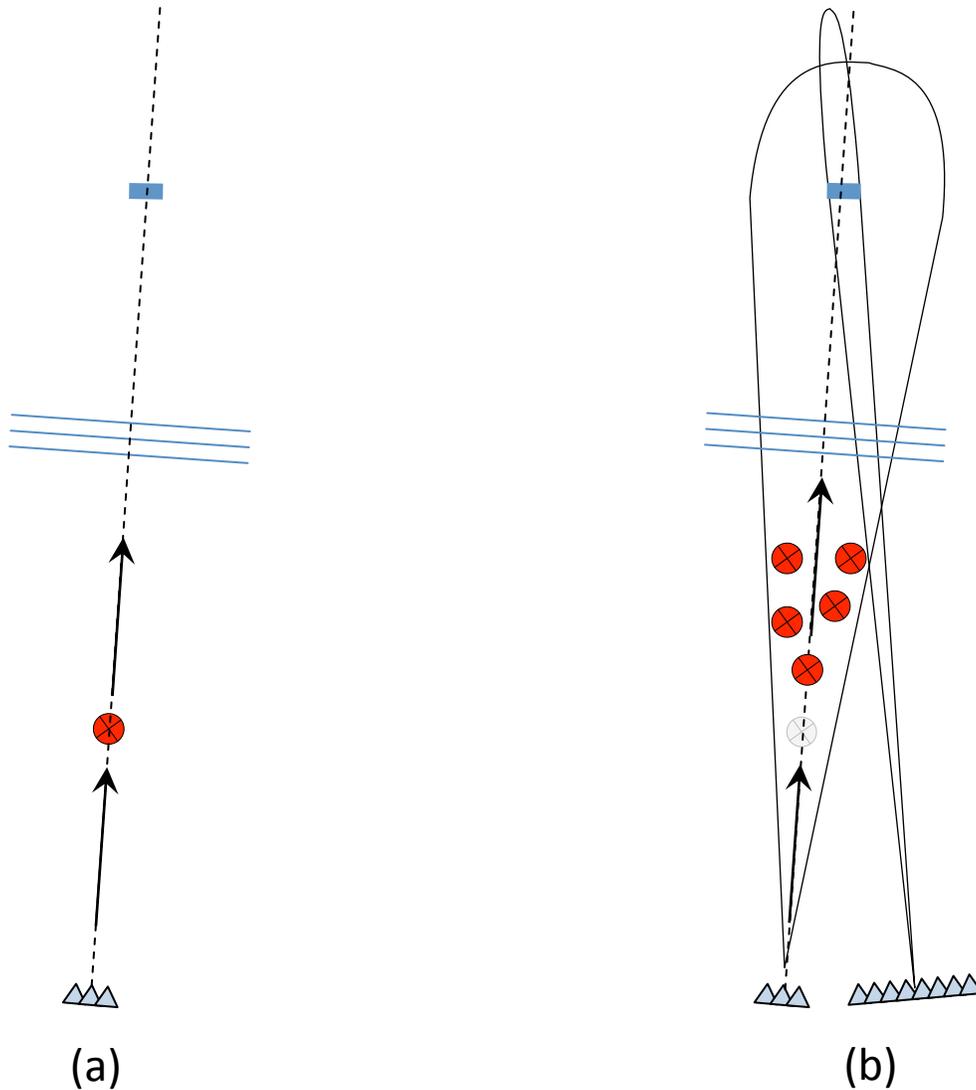
**Table 2.** Standoff Distance (km) From Receive Array,  
Adjusted for Frequency-Dependent Incident Elevation

	Wind farm Size	Standoff (km) Receive Array			
		5 MHz	14 MHz	24 MHz	All Freq
	Incident Elevation	18°	5°	5°	
Front	Single Turbine	15	25	10	<b>25</b>
	Small Farm	25	40	15	<b>40</b>
	Large Farm	35	45	20	<b>45</b>
Back	Single Turbine	10	10	5	<b>10</b>
	Small Farm	15	15	5	<b>15</b>
	Large Farm	15	15	5	<b>15</b>

Small Farm = 25 Turbines, Large Farm = 165 turbines

#### **4 Analysis of the Transmit Path Problem**

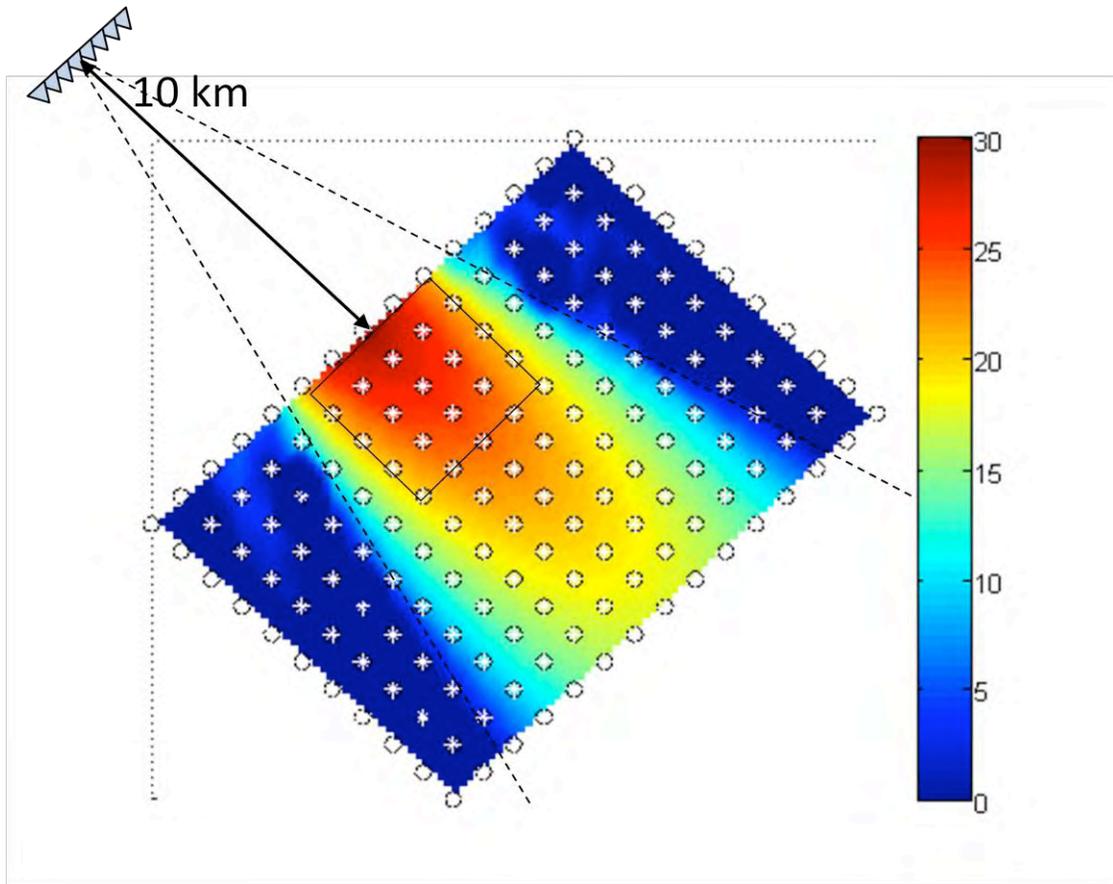
The transmit path analysis is considerably simpler than the receive path for two reasons. First, the smaller transmit array aperture sizes result in a very short distance to the far-field of the transmit array and consequently turbine interactions will likely only occur within the far-field of the full transmit arrays. Second, the additional scatter from the periphery of the transmit beam is rejected by the receive beam sidelobes so there is no beamwidth ratio term. Consequently, the only adjustments to the single turbine scatter modeling is adjustment for distance from the transmit array and summation of the turbines within the intersection of the transmit beam and the wind farm. Therefore, this analysis is of the interaction of a single turbine or multiple turbines with the full transmit array with no focus loss terms. Figure 11 depicts these two modeling scenarios which involve the single turbine interaction and then the multiple (wind farm) turbine interaction.



**Figure 11.** Transmit Path Wind Farm Interference Modeling Steps

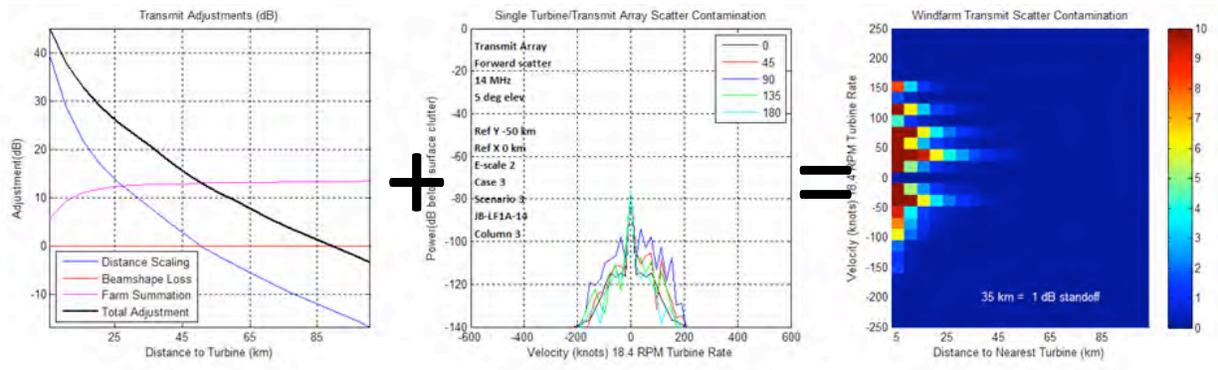
#### 4.1 Transmit Path Modeling

Figure 12 shows the relative transmit scatter responses of an 11x15 field of (165) turbines, at 1 km spacing, starting at 10 km from the transmit array, at 14 MHz. A smaller field of 5x5 is indicated by the box. As in Figure 8, color represents the relative power contribution to the sum, in dB, of each turbine. The relative levels are a combination of the decrease in field strength with distance and off-beam azimuth locations.



**Figure 12.** Relative Turbine Scatter Transmit Array Responses  
14 MHz, turbines in front of array, at 1 km spacing, 10 km from array

Figure 13 plots the results of the analysis for the forward scatter geometry at 14 MHz, for the 5x5 wind farm at 1 km turbine spacing. Figure 13(a) plots the distance scaling and farm summation terms as a function of the distance from the transmit array to the nearest turbine in the wind farm. The distance scaling follows the same conventions as for receive array, and the farm summation is asymptotic to the number of turbines contained in the transmit beam, which approaches 25 (14 dB). Figure 13(b) plots, at a far-field point at 5 degrees elevation, the spectrum of the single turbine scatter normalized to the 0 dB signal level in the absence of the turbine. Figure 13(c) then plots the spectrum incident on the down-range surveillance region as a function of the distance from the transmit array to the closest turbine in the wind farm. Figure 13(c) is plotted as degradation in dB to the reference -70 dB SCV level. The standoff requirement from the transmit array at this frequency, for this size wind farm is 35 km, slightly less than the 40 km required for the receive array.



(a) (b) (c)

**Figure 13.** Full Transmit Array, Distributed Wind farm Contamination  
14 MHz, 18.4 RPM, turbines in front of array, 5x5 turbines at 1 km spacing

**5 Transmit Standoff Distance Requirements**

The calculations described in Section 4 above were carried out for three frequencies of 5, 14, and 24 MHz, for a single turbine, a small 25 turbine wind farm, and a large 165 turbine wind farm to determine a recommended standoff distance from a ROTHr transmit array.

Standoff distances were determined for wind farm turbines in front of the array, behind the array, and for operationally relevant departure elevations. The results are summarized for frequency, elevation, and wind farm size in Table 3 below. As with the case for the receive array, these distances have been adjusted for the relevant frequency-dependent elevation angles.

**Table 3.** Standoff Distance (km) From Transmit Array,  
Adjusted for Frequency-Dependent Departure Elevation

	Wind farm Size	Standoff (km) from Transmit Array			
		5 MHz	14 MHz	24 MHz	All Freq
	Departure Elevation	18°	5°	5°	
Front	Single Turbine	15	15	10	<b>15</b>
	Small Farm	25	35	20	<b>35</b>
	Large Farm	35	45	25	<b>45</b>
Back	Single Turbine	5	5	5	<b>5</b>
	Small Farm	10	5	5	<b>10</b>
	Large Farm	15	5	5	<b>15</b>

## 6 Summary of Recommended Standoff Distances

Table 4 summarizes the standoff distances required for 1 dB SCV degradation at the -70 dB level at all frequencies.

**Table 4.** Minimum Standoff Distances from Transmit and Receive Arrays

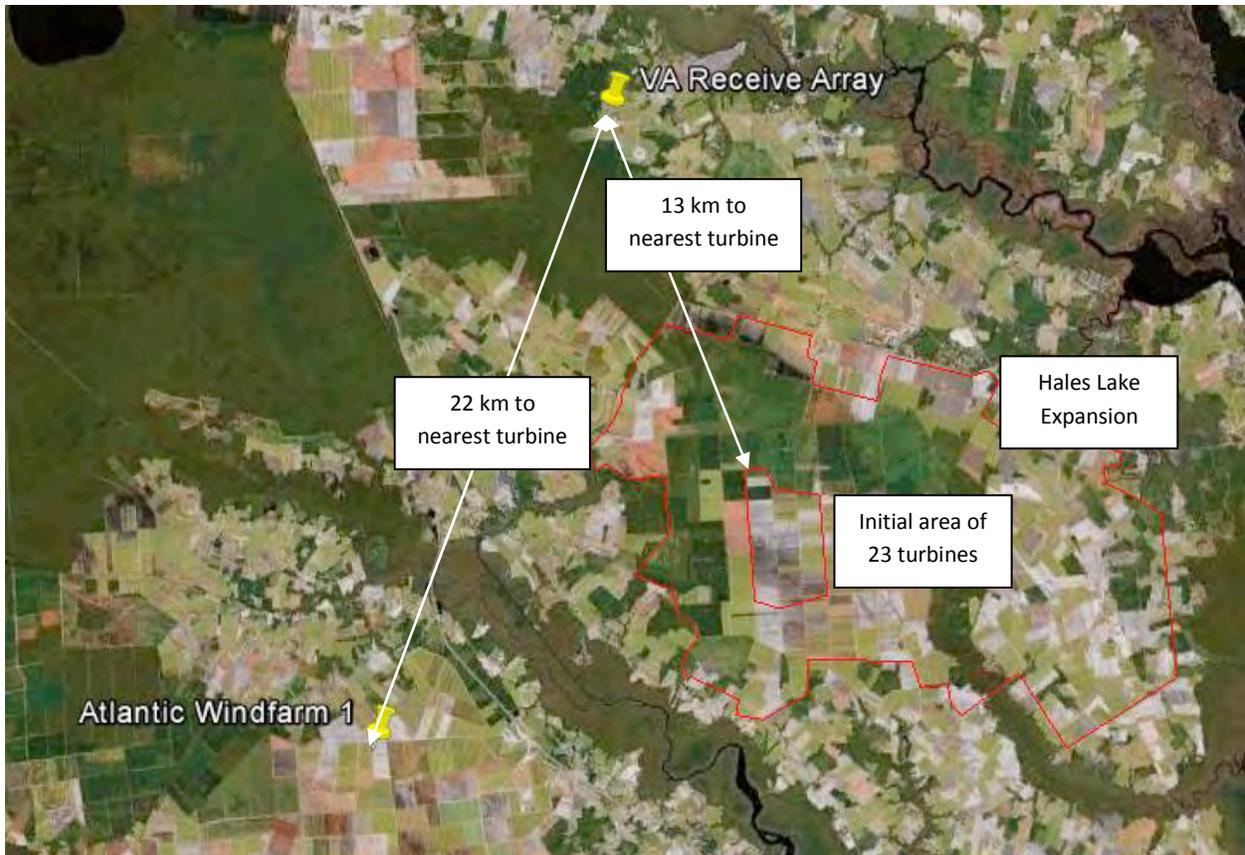
	Transmit		Receive	
	Front	Behind	Front	Behind
Single Turbine	15 km	5 km	25 km	10 km
Small Farm	35 km	10 km	40 km	15 km
Large Farm	45 km	15 km	45 km	15 km

## 7 Specific Proposed Wind farm Predictions

This section summarizes the predicted levels of interference to the Virginia and Texas ROTHr sites from three proposed wind farms. Two wind farm proposals that would affect the Virginia ROTHr receive array is the Hales Lake and the Atlantic Wind installations in North Carolina. The proposed wind farm near the town of Freer, TX would affect the Texas ROTHr receive array.

### 7.1 Hales Lake / Va ROTHr

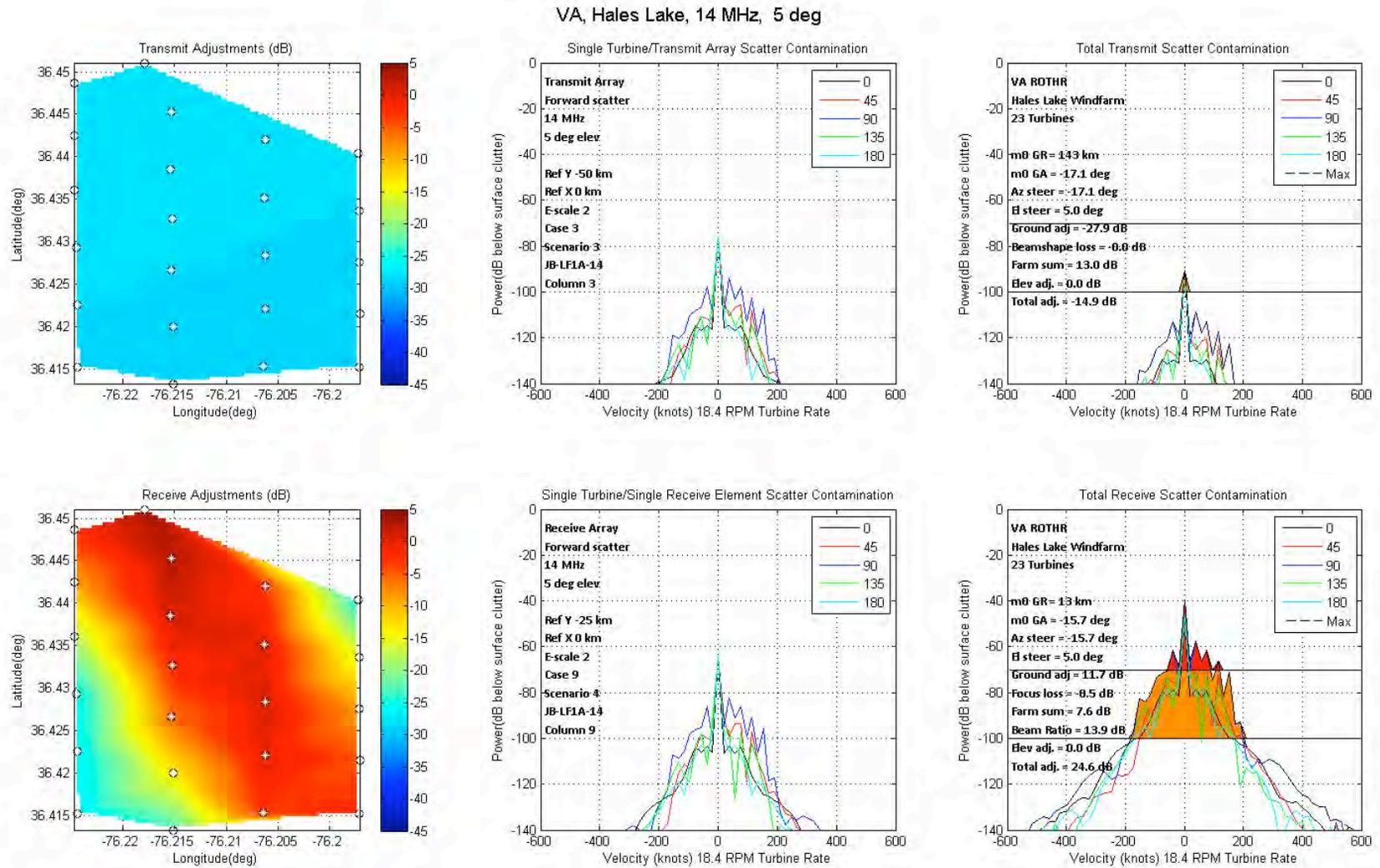
Figure 14 is a Google Earth depiction of the proposed Hales Lakes windfarm project showing both the initial 23-turbine area and a proposed total expansion area.



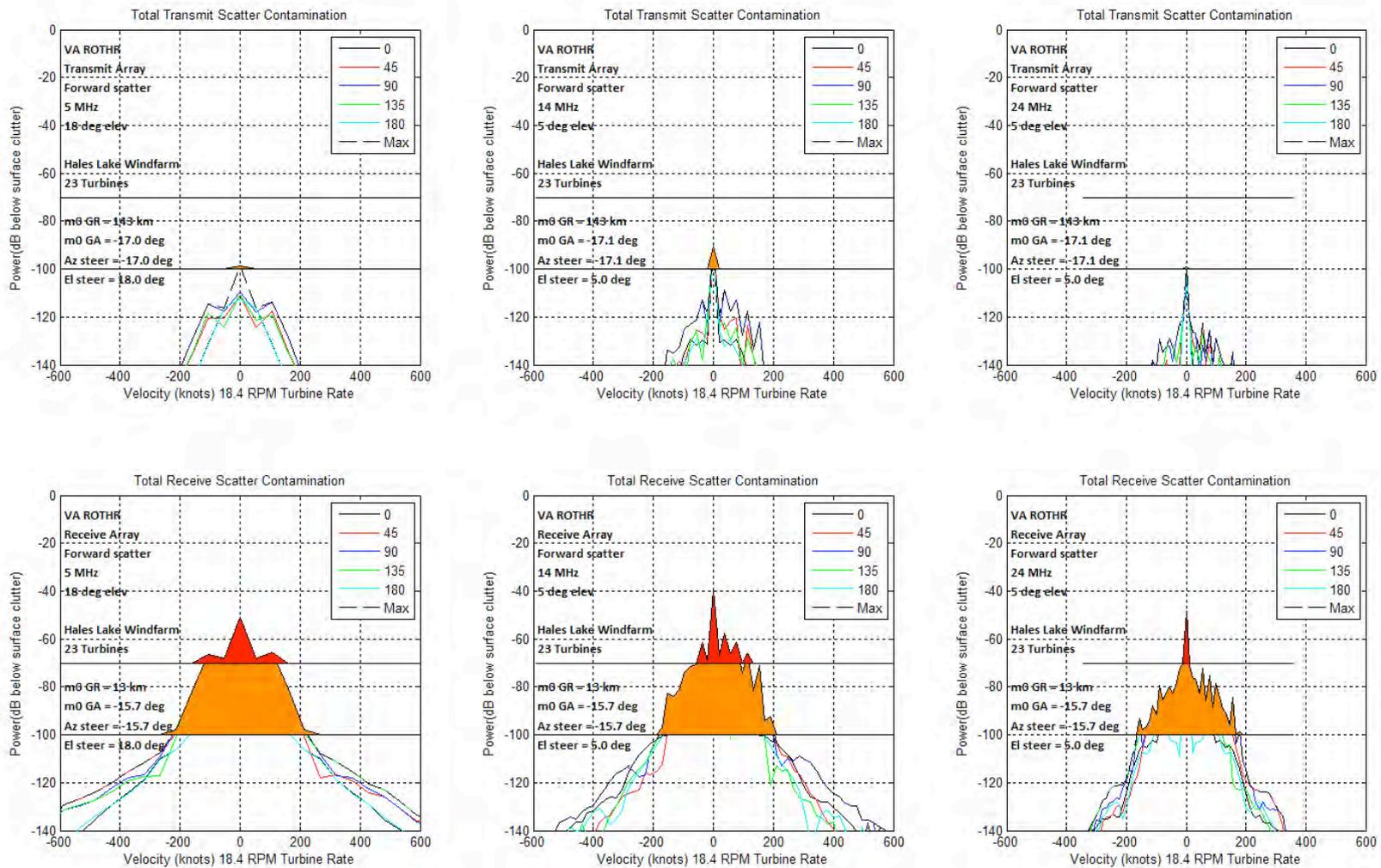
**Figure 14.** Hales Lake and Atlantic Windfarms and Virginia ROTHR Receive Array

Figure 15 depicts the predicted levels of interference at 14 MHz operating frequency of the Virginia ROTHR transmit and receive arrays. The interference is due to scatter off the actual proposed locations for turbines in the Hales Lake project. The top row of plots depicts modulation of the outbound transmit path and the bottom row depicts modulation of the inbound receive path. The ROTHR transmit antenna to turbine distance is 143 km and beyond the recommended 35 km transmit forward-scatter small wind farm standoff range. The prediction indicates no problematic interference. However, the receive antenna to turbine distance is only 13 km, significantly shorter than the recommended 40 km receive forward scatter small wind farm standoff distance. The interference level, indicated by the solid red region above -70 dB, is predicted to be very high for inbound and outbound targets having up to 150 knots radial velocity component or greater. Although not a part of this analysis, the situation will be worse for next generation OTH radars which might achieve interference-free sensitivity to -100 dB below the surface clutter. In this event, the turbine interference on the inbound receive path would mask targets out to about 200 knots radial velocity component, indicated by the solid orange region.

Figure 16 summarizes the 23-turbine Hales Lake wind farm and Virginia ROTHR interference predictions at 5, 14, and 24 MHz. At 5 and 14 MHz, the inbound receive path wind farm scatter will produce significant interference, with worst case occurring at 14 MHz.



**Figure 15.** Predicted Turbine Spectral Contamination at 14 MHz on Virginia ROTH, from Initial 23-turbine Hales Lake configuration

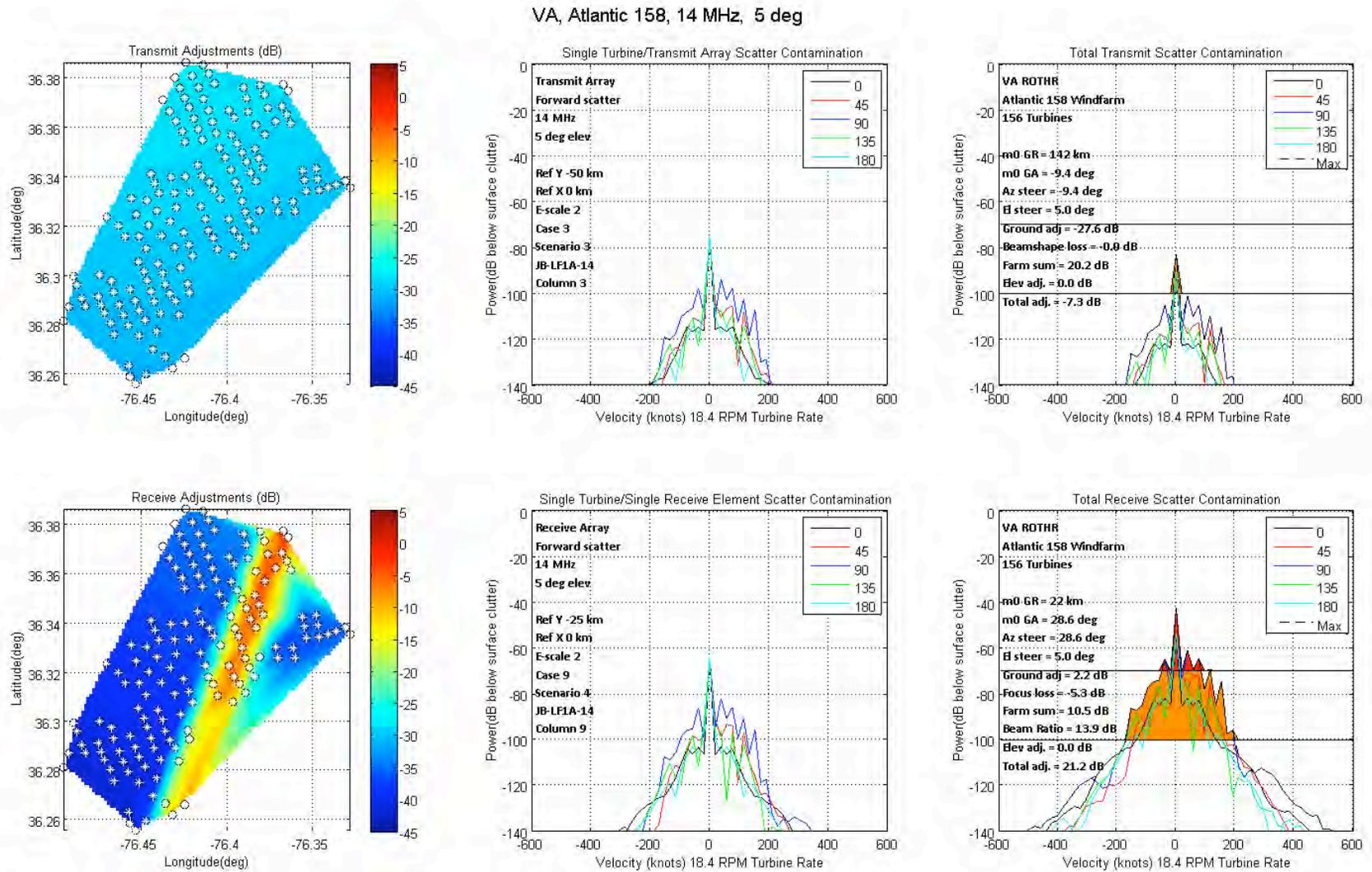


**Figure 16.** Predicted Turbine Spectral Contamination at 5, 14, and 24 MHz on Virginia ROTHF, from Initial 23-turbine Hales Lake configuration

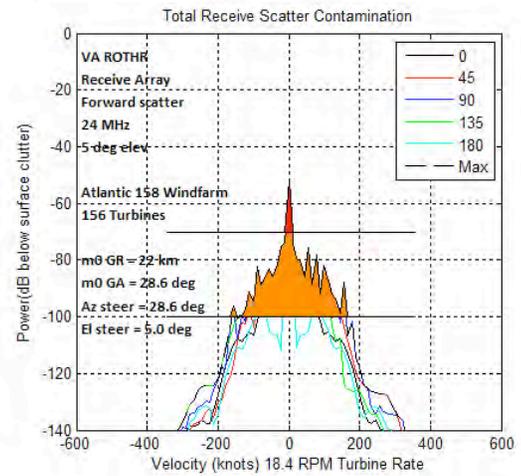
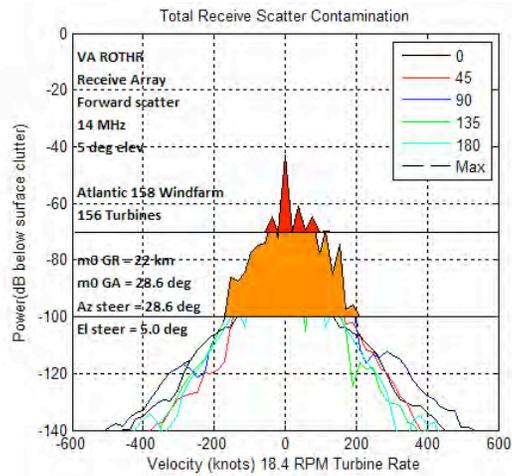
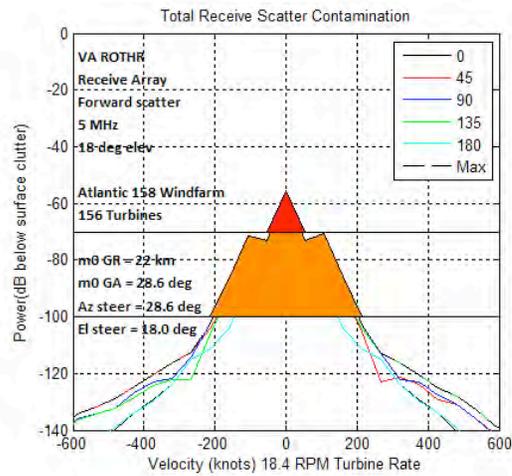
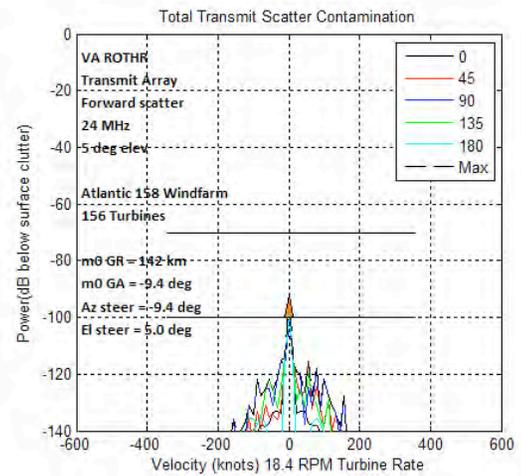
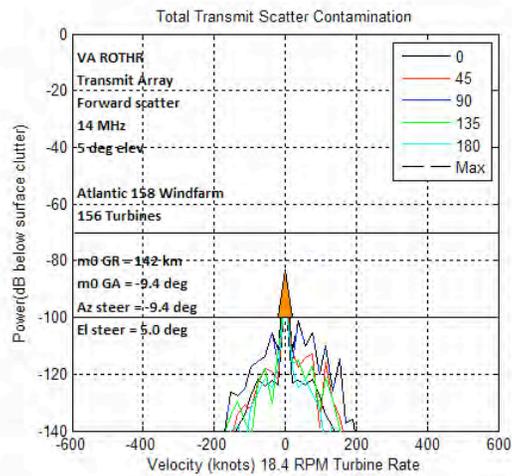
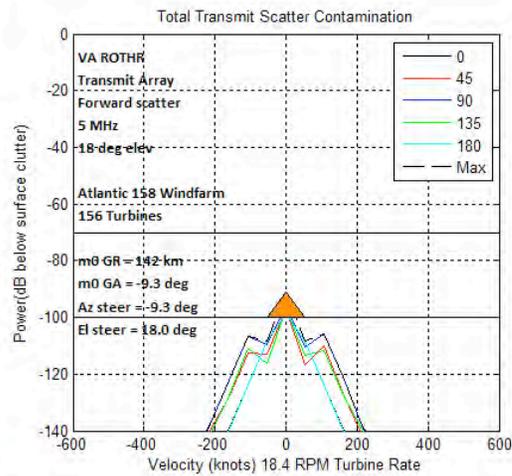
## 7.2 Atlantic Wind/VA ROTH

The precise number of turbines planned for the Atlantic Wind project is under discussion, but the calculations in this section assume 158 operating turbines. Figure 17 depicts the predicted levels of interference, at 14 MHz operating frequency, to the Virginia ROTH transmit and receive arrays from the Atlantic Wind project. The interference is calculated for the actual proposed locations of turbines in the 158-turbine Atlantic Wind project. This project is at a similar range (142 km) from the transmit array, and so the interference from the scatter on the outbound transmit path is insignificant, even though the turbine count is nearly an order of magnitude larger. However, as in the case of the Hales Lake wind farm, the predicted interference from the inbound receive path scatter is a concern. Many of the turbines lie outside of the near-field collimated receive “beam”, as shown by the color-coded relative intensity plotted in the lower left box of Figure 17. The interference contribution from those turbines is 30 dB or so below the contribution from a turbine within the collimated beam. None the less, the total contamination is significant because the turbines are as close as 22 km to the receive array.

Figure 18 summarizes the predicted interference levels at 5, 14, and 24 MHz. The interference from the inbound receive path scatter is severe when the radar is operating around 14 MHz.



**Figure 17.** Predicted Turbine Spectral Contamination at 14 MHz on Virginia ROTHF from 158-turbine Atlantic Wind project



**Figure 18.** Predicted Turbine Spectral Contamination at 5, 14, and 24 MHz on Virginia ROTH R, from 158-turbine Atlantic Wind configuration

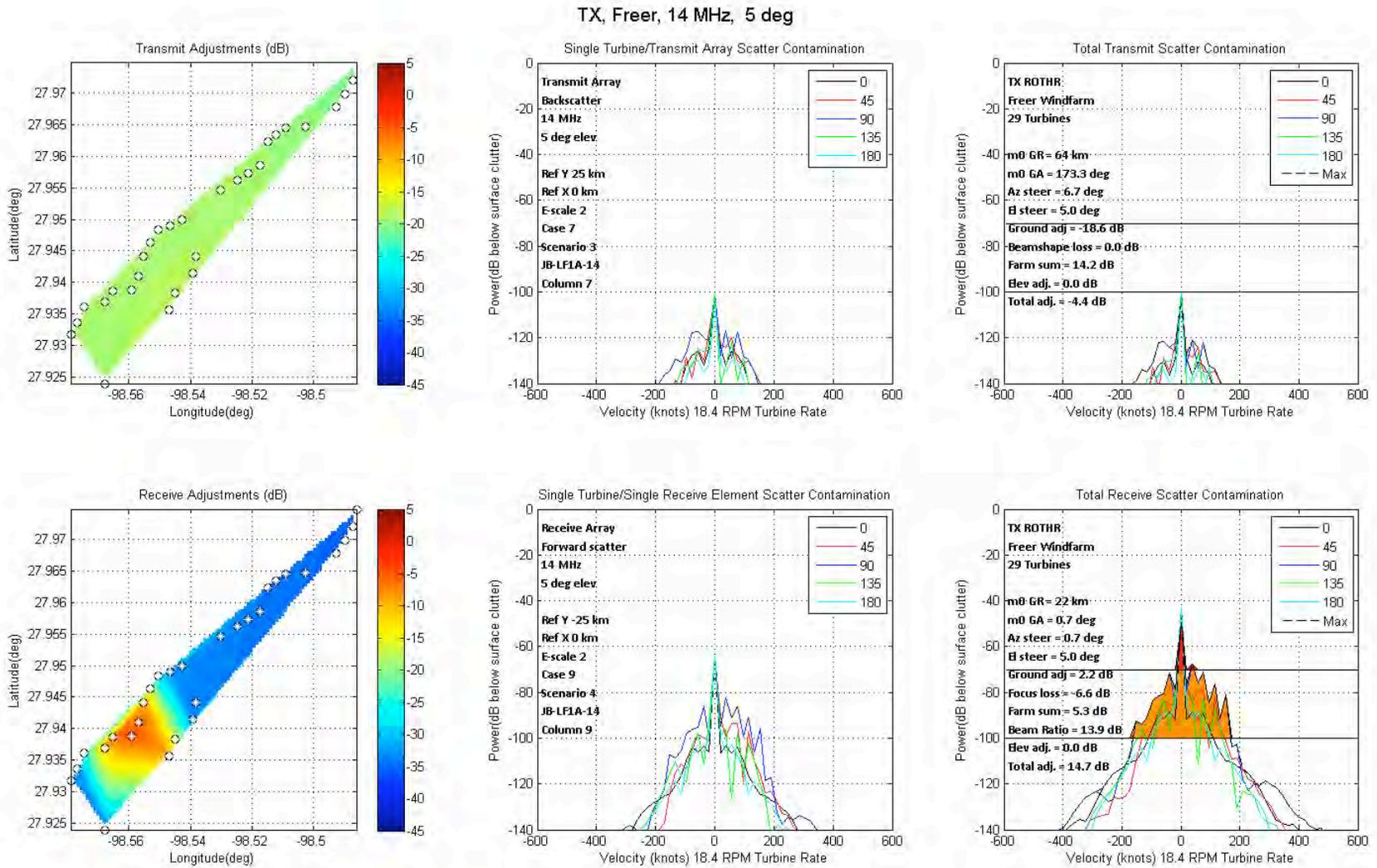
### 7.3 Freer/TX ROTH

Figure 19 is a Google Earth depiction of the proposed Freer, TX, 29-turbine wind farm project. The location is 22 km in front of the ROTH Texas receive array, and 64 km behind the ROTH Texas transmit array. Also shown are the locations of three operational windfarms in Texas: Papalote (87 turbines), Kenedy (118 turbines), and Cedro Hill (100 turbines).

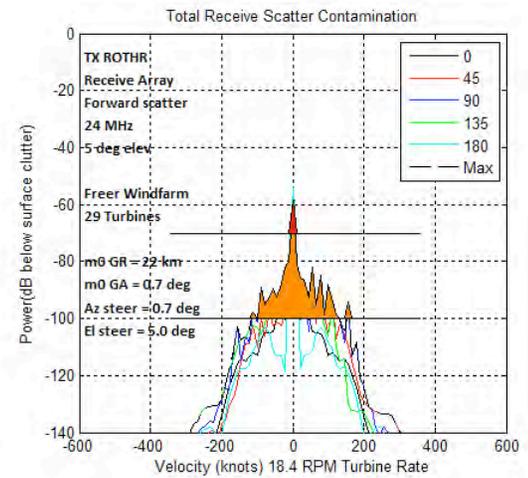
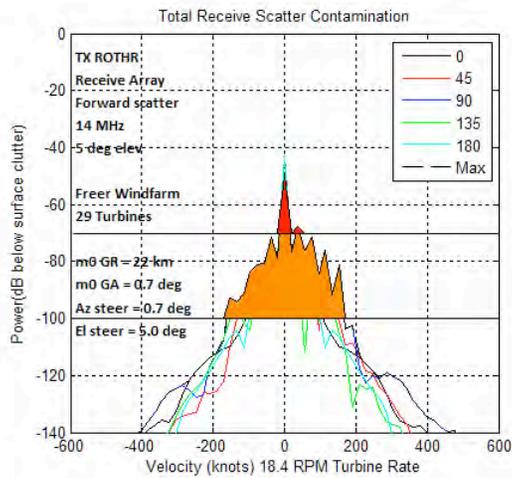
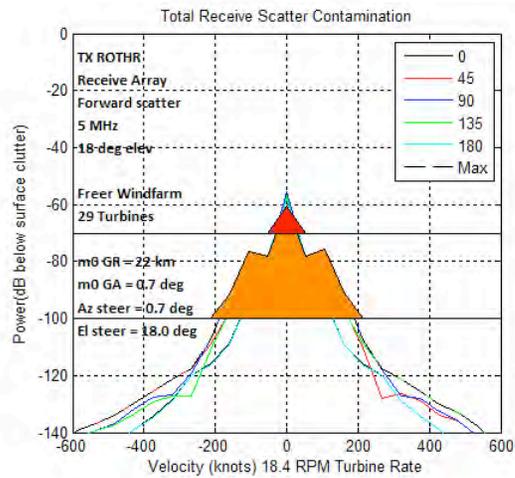
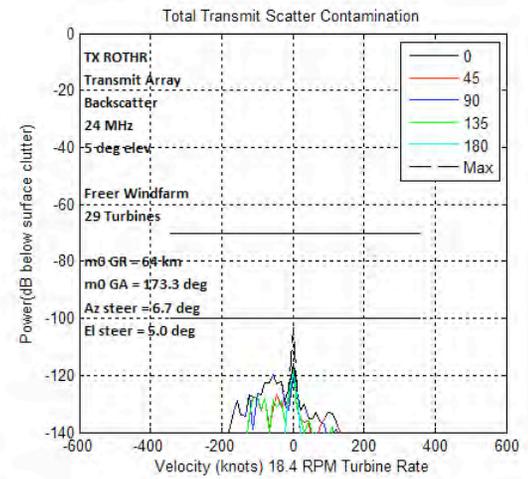
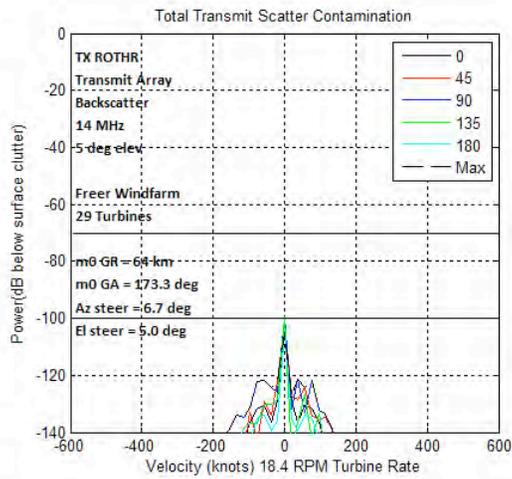
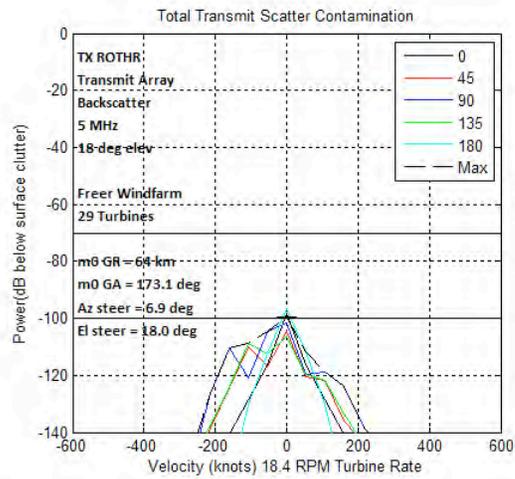


**Figure 19.** Planned and Operational Wind Farms in Vicinity of Texas ROTH

Figure 20 depicts the predicted levels of interference, at 14 MHz operating frequency, to the Texas ROTHR due to scatter off the actual turbine locations in the Freer wind farm project. The ROTHR transmit antenna to turbine distance is 64 km, which is well beyond the recommended 10 km transmit backscatter small wind farm standoff range, and the prediction indicates no problematic interference. The receive antenna to turbine distance is only 22 km and within the recommended 40 km receive forward scatter small wind farm standoff distance. The interference level, indicated by the solid red region above -70 dB, is predicted to be observable for inbound and outbound targets up to roughly 100 knots radial velocity component. As noted, the situation will be worse for next generation OTH radars which might achieve interference-free sensitivity down to -100 dB below the surface clutter. In this event, the turbine interference on the inbound receive path would mask targets out to about 200 knots. Figure 21 depicts the interference at 5, 14, and 24 MHz.



**Figure 20.** Predicted Turbine Spectral Contamination at 14 MHz on Texas ROTHF, from 29-turbine Freer, TX project



**Figure 21.** Predicted Turbine Spectral Contamination at 5, 14, and 24 MHz on Texas ROTH, from 29-turbine Freer, TX configuration

## **8.0 Summary**

This report has described an analysis of wind turbine interference to current generation operational OTH radar systems. The report is based on detailed and comprehensive modeling of a generalized wind turbine generator structure, its electromagnetic interaction with a range of OTHR operational frequencies and the impact this interaction is predicted to have on OTHR signal processing. The required standoff distances presented in Table 4 represent a generic earth propagation path and worst case turbine rotor orientation. Any deployment of one or multiple wind turbine generators (wind farms) within these standoff distances will require specific and detailed analysis to determine the extent of impact to an affected OTHR system.

This report has also provided an assessment of the impact of proposed wind farms near operational ROTH system sites in Virginia and Texas. The analysis used generalized analysis parameters combined with the latest available wind turbine proposed locations and found that each proposed wind farm installation will cause interference to the existing OTHR operations to the extent shown. A more detailed analysis of each existing, and most importantly, proposed wind farm layout is required to provide a formal assessment of operational degradation and impacts to mission.

## **9.0 References**

1. Wind Turbine Impact on High Frequency Skywave Radar (Estimated Standoff Distance) v4, August 11, 2011, Serafin Rodriguez (NRL), Yuri Abramovich (WR Systems, Ltd.), Rod Barnes (WR Systems, Ltd.), NRL Report NRL/MR/5320--11-xxxx
2. Executive Report, Stand-Off Requirement of Wind Turbines from Relocatable Over The Horizon Radar (ROTHR) Systems, ROTHR Program Office, October 2011
3. Wind Turbine RF Wave Scattering at HF Frequencies: Doppler Analysis of the Relocatable Over The Horizon Radar (ROTHR) Case - v 1.0, Fernando Beltran, Consultant, June 2012
4. NEC4 code is Licensed by: Lawrence Livermore National Laboratory, P.O. Box 808, L-795, Livermore, CA 94551, Industrial Partnerships Office
5. NEC Turbine Model Validation, Ver 1.0, Fernando Beltran, Consultant, December 6, 2011
6. GRWAVE, Groundwave Propagation analysis calculation software is available from the International Telecommunication Union Study Group 3 (SG 3) - Radiowave propagation