

503 IMPROVED CAPABILITIES FOR SITING WIND FARMS AND MITIGATING IMPACTS ON RADAR OBSERVATIONS

Steven R. Chiswell*
Savannah River National Laboratory, Aiken, SC

1. INTRODUCTION

The development of efficient wind energy production involves challenges in technology and interoperability with other systems critical to the national mission. Wind turbines impact radar measurements as a result of their large reflectivity cross section as well as through the Doppler phase shift of their rotating blades. Wind farms can interfere with operational radar in multiple contexts, with degradation impacts on: weather detection such as tornado location, wind shear, and precipitation monitoring; tracking of airplanes where air traffic control software can lose the tracks of aircraft; and in identification of other low flying targets where a wind farm located close to a border might create a dead zone for detecting intruding objects.

Objects in the path of an electromagnetic wave affect its propagation characteristics. This includes actual blockage of wave propagation by large individual objects and interference in wave continuity due to diffraction of the beam by individual or multiple objects. As an evolving industry, and the fastest growing segment of the energy sector, wind power is poised to make significant contributions in future energy generation requirements. The ability to develop comprehensive strategies for designing wind turbine locations that are mutually beneficial to both the wind industry that is dependent on production, and radar sites which the nation relies on, is critical to establishing reliable and secure wind energy. The mission needs of the Department of Homeland Security (DHS), Department of Defense (DOD), Federal Aviation Administration (FAA), and National Oceanographic and Atmospheric Administration (NOAA) dictate that the nation's radar systems remain uninhibited, to the maximum extent possible, by man-made obstructions; however, wind turbines can and do impact the surveillance footprint for monitoring airspace both for national defense as well as

critical weather conditions which can impact life and property. As a result, a number of potential wind power locations have been contested on the basis of radar line of site. Radar line of site is dependent on local topography, and varies with atmospheric refractive index which is affected by weather and geographic conditions.

2. RADAR LINE OF SITE DETERMINATION

Radar line of site is commonly assessed using a standard atmosphere assumption. The vertical refractivity gradient for the standard atmosphere is:

$$\frac{dn}{dh} = -40 \times 10^{-6} \text{ (Battan, 1981)}$$

Figure 1 (Vogt, 2007) illustrates the radar line of site within 425 feet of the ground determined for National Weather Service (NWS) NEXRAD radar locations based on standard atmosphere refractivity with a 1.0° beam width and 0.5° elevation angle and incorporating local topography. An object would be within the radar's line of sight if the combination of its height and the elevation difference between the ground at the radar and the base of the object is greater than the

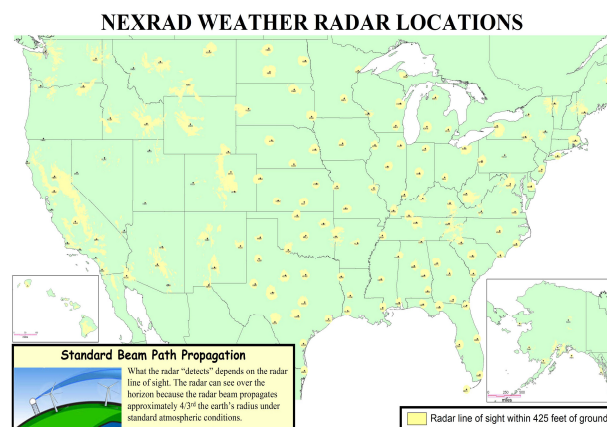


Figure 1. NEXRAD line of site (Vogt, 2007). Yellow filled areas show where the beam elevation is within 425 feet of the ground.

* Corresponding author address: Steven R. Chiswell, Savannah River National Laboratory, Savannah River Site, Aiken, SC 29808; email: steven.chiswell@srnl.doe.gov

base of the radar beam.

The atmospheric refractive gradient may depart substantially from the conditions assumed above however. Analysis of the atmospheric dependency of refractivity gradients has shown that vertical moisture gradients provide the most significant contribution to the departure from the standard atmosphere model, while temperature inversions provide an additional significant component to this anomalous propagation (Gao, 2005, Stagliano, 2009). A survey of four locations within the United States selected from various climate regimes (Gao, 2005) showed that significant departures from the Standard Atmosphere computed effective solution occurred between 10 and 30 percent of the time, and that the conditions responsible for the departures were more likely to be conditions important to severe weather events. In the case of wind farms which are most likely to contaminate low elevation radar scan levels, topographic model resolution, in addition to atmospheric refractivity, is also important (Kucera *et al.*, 2004, Stagliano *et al.*, 2009).

Although wind farm interference with radar is well documented, it is important to have quantitative metrics to determine, in given situations, the impact of this interference on the required radar performance. At present, many of the wind farm installations within the United States are in areas with relatively low moisture gradients such as the great plains and mountain ridges (Figure 2).

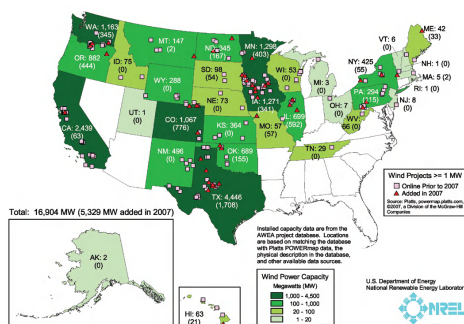


Figure 2. Location of wind power installations and project locations as of 2007 (US DOE, NREL).

However, to realize the goal for greater wind power production, an increased interest is being placed on coastal and border locations where additional wind power capabilities exist (e.g. Figure 3).

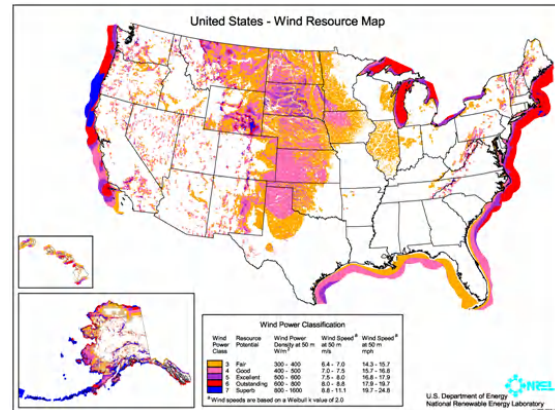


Figure 3. United States Department of Energy wind power resource potential map.

Accompanying the greater Radar line-of-site afforded by the coastal and offshore locations is a greater propensity for atmospheric attenuation due to marine boundary layer moisture gradients as well as thermal inversions where the traditional standard atmosphere approach to siting limitations is not well suited. These situations therefore require the use of explicit calculations of the refractive index of the atmosphere. Bevis *et al.* (1994) have shown it is possible to quantify the uncertainty in refractivity equation:

$$N = (n - 1) \times 10^{-6} = k_1 \frac{P}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$

such that ray tracing of the radar beam can be used to determine the actual impact of wind farms.

3. DEVELOPING AN ATMOSPHERIC REFRACTIVE GRADIENT CLIMATOLOGY

In order to help meet the recent goal established for increasing the capability for 20% wind energy by the year 2030 (US DOE 2008), the ability to develop comprehensive strategies for designing wind turbine locations that are mutually beneficial to both the utilities that rely on their production, and the radar sites which the nation relies on, is critical to establishing reliable and secure wind energy. Moreover, as wind energy development looks to offshore locations where super-refractive conditions are common, the development of site specific radar line of site determination is necessary to provide the optimal balance between future energy development and radar requirements.

Figure 4 illustrates the relationship between refractive gradient and radar beam height as a function of distance. Super-refractive conditions exist where the refractive gradient is less than -40 km^{-1} , and ducting, where the radar beam will be bent back towards the ground, occurs below approximately 156.9 km^{-1} . As can be clearly seen, for super-refractive conditions, the distance at which an object of a given height may be visible to radar increases substantially at lower beam elevation angles as the refractive gradient increases. In order to accurately determine the likelihood of radar contamination, the probability of local conditions placing the wind farm within the radar footprint is an important consideration. Towards this effort, a climatologic analysis of atmospheric refractivity is being developed for use in wave propagation models to determine the conditions and frequency of those conditions that negatively impact radar.

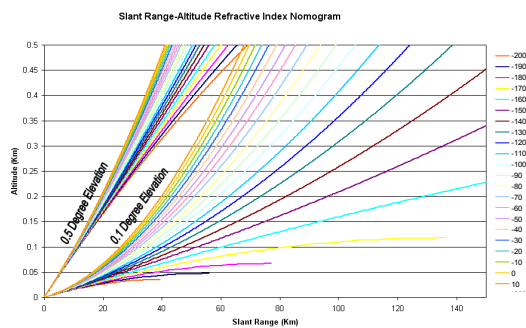


Figure 4. Radar beam height as a function of distance for elevation angles of 0.5° and 0.1° .

Previous studies (e.g. Staglino, 2009) which used balloon soundings in order to calculate the vertical gradient of refractive index have noted that it is difficult to capture the lowest levels of the profile due to limitations in data from operational collections. Alternatively, high resolution numerical models can be useful in resolving vertical structure near the ground, though interpolated pressure level output again is generally too coarse in areas of complex terrain and very shallow features. Several alternative methods, including internal model routines, have been proposed to allow the native model vertical resolution to be utilized.

For the development of this climatology, the Rapid Update Cycle (RUC) model (Benjamin, 2004 & 2007) is used. The RUC model is able to assimilate a wide range of observations, including

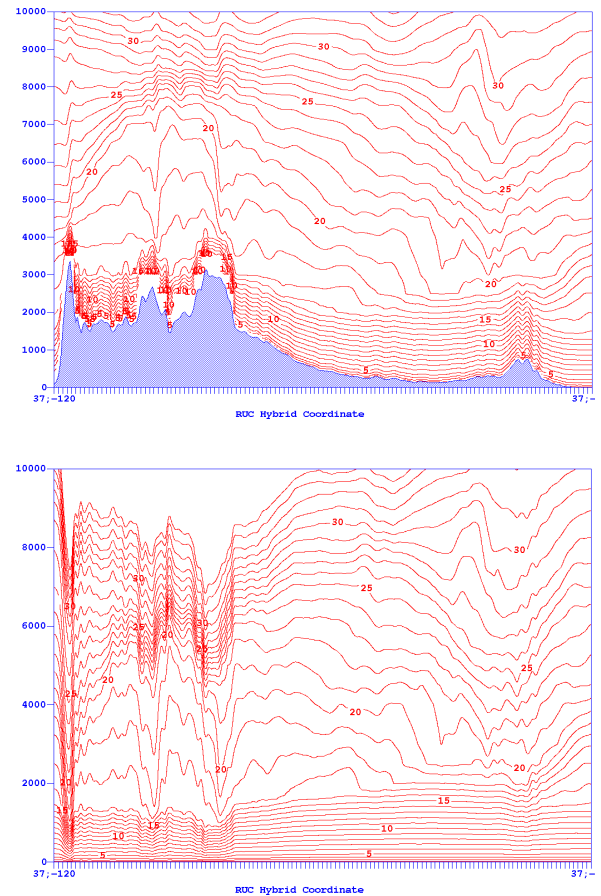


Figure 5. RUC 13km model vertical coordinate cross section at 37°N . Top panel, native hybrid levels as a function of elevation (meters); Bottom panel, hybrid levels as a function of height (meters) above ground level.

local mesonet and aircraft observations which will enable the lowest model layers to most accurately depict conditions along the radar line of sight where wind turbines operate. The hourly RUC model analyses enable a comprehensive climatology of local site conditions affected by local geography and meteorological conditions. The native vertical coordinate of the RUC model is a hybrid isentropic/terrain following coordinate which is produced operationally by NOAA's National Centers for Environmental Prediction (NCEP) and disseminated widely in that format. By utilizing the native model hybrid level output for refractivity calculations, the full model vertical resolution is able to be exploited. As seen in figure 5, the model vertical coordinate is self-adjusting to maintain vertical separation. When viewed relative to height above ground level, the self adjusting spacing of the coordinate is clearly seen. The lowest 5 vertical levels are generally within 200 m of the surface, providing adequate vertical

resolution for assessing the refractivity climatology.

Figure 6 provides an illustration of the application of the refractivity fields produced from the RUC analysis at 12 UTC, February 18, 2009. Utilizing the refractive gradient between 10 and 20 meter above ground level, the locations being impacted by significant super-refractive and ducting conditions are highlighted.

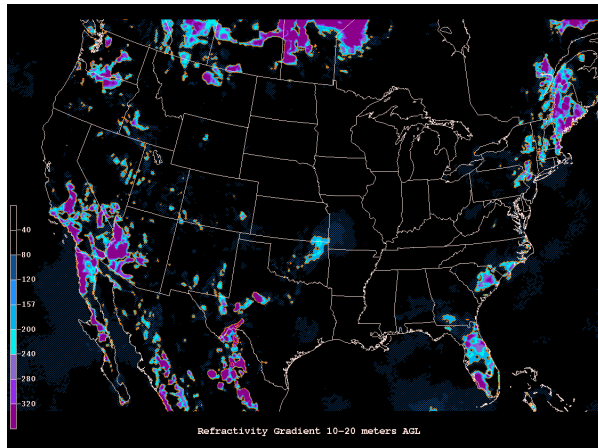


Figure 6. Refractivity gradient analyzed from RUC hybrid levels at 10-20 m above ground level at 12 UTC, Feb 18, 2009.

The Morehead City, NC radar (Figure 7) confirms that ducting conditions were affecting the radar during the morning of 18 February, 2009 as can be seen from the cyclic reflection of the radar signal to the south and west of the radar location, especially along the coast. The profile of the index of refraction and temperature/dewpoint profiles occurring within this region are shown in Figure 8 which compares *in-situ* sounding and model analysis. The impact of the surface inversion and low level moisture capped by drier air above the inversion creates strong super-refractive conditions at this location

4. RESULTS

The use of RUC hybrid level output for computing atmospheric refractivity has shown to provide a useful diagnostic capability in developing the refractivity climatology. This climatology will be used in development of assessments and mitigation strategies which can be applied using local conditions. There are currently a number of wind farms that are within line of site of existing NOAA Doppler weather radars. These wind farms

are situated at a range of distances, and therefore will provide quantitative evaluation of impact forecasts using refractivity analysis. Many current mitigation strategies are based on post-processing software to remove artifacts and to employ anomalous propagation filtering and correction methods. Providing predictive propagation fields would allow radar systems as well as processing systems to adaptively apply mitigation strategies in a more efficient manner. In the extreme case where exclusion zones are employed, these periods could be determined in advance such that their automated use would be minimized.

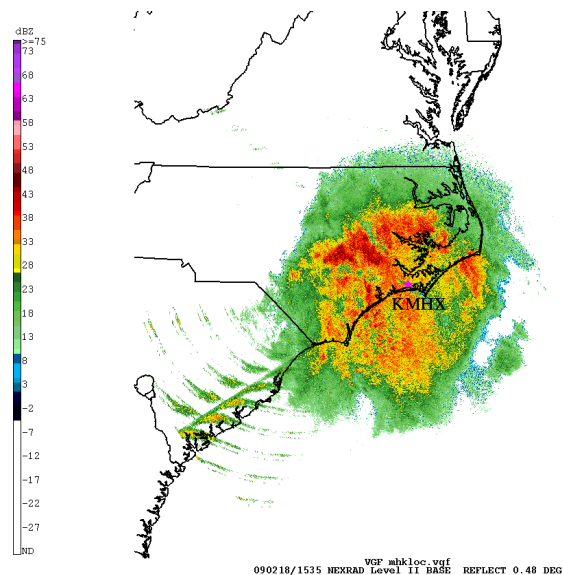


Figure 7. Morehead City, NC NEXRAD radar image at 15Z, Feb 18, 2009.

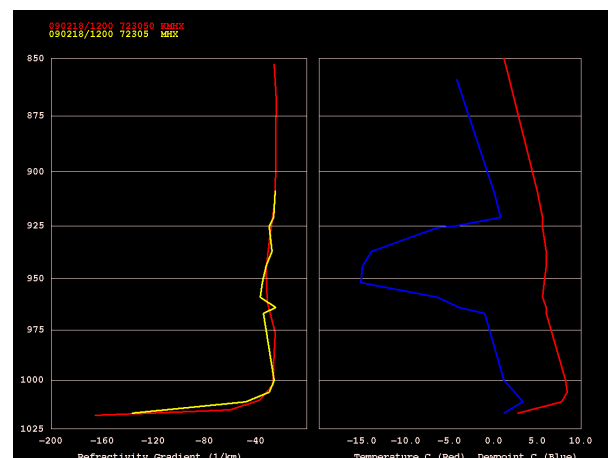


Figure 8. Morehead City/Newport, NC refractivity profile (left) showing balloon sounding profile (yellow) and RUC analyzed (red). Right panel shows observed temperature and dewpoint (Celsius) profiles.

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