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WIND FARMS AND THEIR EFFECT ON RADIO NAVIGATION AIDS

Simbo A. Odunaiya
Ph.D.

Ohio University
Athens, Ohio 45701
Tel: (740) 593-1531
Fax: (740) 593-1604
E-mail: odunaiya@ohio.edu

ABSTRACT

Electric power generation from wind is becoming a more important source of energy nowadays. Recently, there has been a drastic increase of wind farms used as alternative energy facilities. In the United Kingdom, it is expected that 10% of the electric supply will be from renewable sources by the year 2010. A substantial amount of this 10% target is expected to be met by wind energy. The British Wind Energy Association (BWEA) has conservatively estimated that this could represent around 4,000 turbines in both onshore and offshore locations. Between the years 2003 and 2005, over 3700 cases of wind-turbines have been studied by the Federal Aviation Administration (FAA). These wind-farm facilities consist of any number of significantly tall towers holding equally large turbines. Electric power is generated by the rotation of the large turbines installed on the tall towers. Because of the physically large turbines and the height of the supporting towers, the wind farms can have an effect in the aviation domain. The wind farm can constitute a potential source of degradation to radio navigation-aid signals in two different ways. The first is the shadow effect due to the size and extent of the wind-turbine. The second effect is due to multipath from both the stationary and rotating parts of the wind-turbine. With the rate of development of the wind farm industry, it is important to understand and properly characterize the effect of the wind farm on navigation systems, to ensure both the safe operation of the navigation systems and best utilization of the wind energy. This paper will analyze the potential effects of wind farms on the VHF Omni-range (VOR) using a physical optics model. The conclusions from the paper will demonstrate that new guidelines are necessary to deal with siting issues for the many farms that will soon become prevalent in order to safeguard the integrity and reliability of radio navigation-aid signals.

BACKGROUND

Navigation Systems and Multipath

Navigation and landing systems are usually susceptible to multipath from large structures located in proximity to the radiating source of the systems. Some particular navigation aids of interest employ ground based components that are known to be susceptible to multipath interference. These include:
- Non-Directional Beacons (NDB)
- Distance Measuring Equipment (DME)
- Instrument Landing System (ILS)
- Microwave Landing System (MLS)
- VHF Omni-directional Radio Range (VOR) and
- Tactical Air Navigation (TACAN)

The effect of multipath interference can sometimes result in out-of-tolerance conditions for the navigation aid or landing system of interest. To this effect it is important when siting navigation and landing systems to study and make sure that these effects and others are in fact minimized. When the system is already operational, potential sources of interference like large buildings and other structures must be sited in such a way that their impact on the operational system is minimized. The FAA publishes siting manuals for each of these navigation aids that outline the guidelines when a new system is being sited or when a structure is being proposed near an existing system. A large structure like a wind turbine falls in the domain of structures that must be properly studied before they are sited near navigation aids.
In considering the potential effects of structures and ensuring that an Air Traffic Service (ATS) provider can take the appropriate measures to satisfy safety requirements, it is necessary to consider the siting criteria applicable to the particular navigation aid. This paper will use the example of the VOR.

VOR Siting Criteria

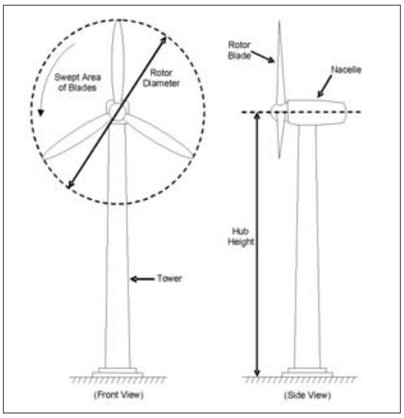
The FAA order 6820.10[1] specifies the siting criteria for VOR, VOR/DME, and VORTAC (VOR co-located with TACAN). A study of wind turbine generators cited in this study[2] indicated that VOR and DVOR facilities will experience no significant degradation of performance due to the presence of wind- turbine generators if the generators are cited in accordance with FAA standard guidelines for objects near VOR and DVOR facilities.
The standard guidelines for objects near VOR and DVOR facilities require that
1) Only crop raising and grazing are allowed within 1000 feet of the VOR except at mountain top sites where these activities must be restricted to area below and off the counterpoise,
2) Single trees of up to 30 feet are tolerated beyond 500 feet,
3) Wire fences should not subtend and angle more than 0.5 degrees from the horizontal measured from the antenna,
4) Overhead power and control lines may be installed beyond 600 feet of the VOR antenna but must remain essentially radial,
5) No structures shall be permitted within 1000 feet of the antenna, and
6) All structures that are partly or entirely metallic shall subtend vertical angles of 1.2 degrees or less, measured from the ground elevation of the VOR antenna. Wooden structures with negligible metallic content may be tolerated if subtending vertical angles less than 2.5 degrees.
The wind turbine will definitely fall under criterion number 5 above. This paper will show that this criterion must be reviewed with regards to wind turbines, especially when these wind-turbines are located in clusters known as wind farms.

Wind Turbines

The effect of wind farms on navigation systems will be influenced by the physical characteristics, operational parameters, and siting of the wind turbines. This section describes these features for typical wind turbines. The rate of growth in the number and size of wind farms in the US is also discussed, in order to show the potential impact on the NAS.

General Description

A wind turbine is a machine used to convert the kinetic energy of the wind into electricity. Most modern wind turbines use a three-bladed rotor turning on a horizontal axis, as shown in Figure 1. An enclosure called a nacelle holds the drive shaft, generator, gearbox, and controller and is mounted at the top of a large tower, behind the hub of the rotor. The entire nacelle and rotor assembly turns as needed to face into the wind. The pitch of the blades may be varied in order to regulate the speed of rotation, and electromagnetic and/or mechanical braking may also be used.



Modern large-scale rotor blades are usually made of composite materials such as fiberglass or carbon fiber embedded in polyester or epoxy resin. Older or smaller wind turbines may utilize other materials such as steel, aluminum, or wood. The support towers may be concrete, steel mesh, or tubular steel, with the latter being the style of choice for today's large turbines.

Wind turbines come in all sizes, but those used for commercial operations typically have rotors measuring 150 to 250 feet in diameter, placed on towers of similar height. Having larger rotors allows the generation of more electricity per turbine and/or the utilization of lower wind speeds. Since many other costs associated with constructing a wind turbine increase only slightly with size, the economics of scale encourage the development and construction of ever-larger wind turbines. For offshore installations, where noise and visual impacts may be less of a problem, rotors may be as large as 400 feet in diameter.

The capability of an object to intercept and return radio energy depends upon the size, shape, orientation, and reflectivity of the object. The reflectivity of a wind turbine depends on the materials of which it is composed. In general, this ability to reflect increases with the size of an object, such that a large wind turbine may be expected to reflect more signal. In a similar manner the ability of an object to create blockage between a signal source and the reception point also depends largely on the size and shape of the object.

Siting

Wind turbines may exist singly, in a small cluster, or in a large collection known as a wind farm. A large wind farm is shown in Figure 2. The accepted practice in constructing wind farms is to site the wind turbines in rows perpendicular to the prevailing wind direction. The turbines are spaced three to five rotor diameters apart along the row, and five to ten rotor diameters apart between rows. The spacing may become more equidistant if the wind does not always come from the same direction. Terrain is also taken into consideration. Since the wind speed is greater at higher elevations, and also gains force as air is pushed up the side of a hill, wind turbines are located on tops of hills or ridges wherever possible.

Local or state regulations may establish minimum setbacks from roads, houses, and other buildings. On the federal level, the FAA currently treats wind turbines the same as any other physical obstruction.

It is recognized that wind turbines do not transmit or radiate other than the generation of background noise similar to any non-transmitting electrical device. However, the physical characteristics of a wind turbine and its operation are known to have an effect on the performance of primary radar [3]. With respect to navigation aids, the impact on performance is less obvious but could be of a similar nature. In essence, the siting of wind turbines in close proximity to a navigation aid may result in an effect on the coverage of the radiated signals.

Figure 2. Wind turbines at the Stateline, Wind Project in Oregon.

Growth Rate

The number of wind farms across the country has been increasing in recent years. Table 1 shows the increase in installed wind generation capacity since 2000, according to the American Wind Energy Association (www.awea.org). Much of the year-to-year variation in installed capacity can be attributed to the fact that a federal wind-energy-production tax credit has been allowed to lapse in alternate years.

Table 1. Installed wind energy capacity in the U.S.

Year	Installed (MW)	Decommissioned	Total (MW)
2000	67	0	2578
2001	1697	0	4275
2002	446	36	4685
2003	1687	0	6372
2004	389	21	6740

The FAA must determine whether proposed wind-turbine construction would cause an obstruction hazard to air traffic. Table 2 shows the number of new wind-turbine cases since 2003 that have been studied by the FAA. Although there was a decline in cases for 2004, it appears that there will be a large number of cases presented in 2005.

Table 2. Number of new wind turbine cases since 2003

Year	2003	2004	2005
Number	1645	945	1133 (through mid-March)

ANALYSIS

Computer Modeling now used extensively is the analysis of Navigation and Landing Systems, has proven to be a cost-efficient and relatively risk-free method of predicting system performance given various multi-path environments. Ohio University has a collection of different models that can be used for the analysis of Navigation and Landing systems in the presence of different potential sources of multipath. This analysis makes use of one such model, the Ohio University Navigation and Landing Performance Prediction Model (OUNPPM).

The OUNPPM, which is based on the theory of physical optics (PO), has been used to analyze the performance of a proposed wind farm near an operational VOR. The PO technique is a high frequency technique used to compute approximations to the electric fields reflected from surfaces, with the currents on the surface determined by electric fields based upon Snell's law of reflection.

Assumptions made in the algorithm are:

1) Reflections are assumed to be in the forward scatter direction only,
2) Multiple scattering is not considered, and
3) Diffraction of signals at the edges of ground planes are considered as second order effects and as such negligible

The OUNPPM has been validated through several applications and it is known to be a quite reliable model.

Modeling

In order to properly analyze the effect of the wind turbine on VOR performance the different parts of the wind turbine have been simulated separately in the model. Figure 3 shows the different parameters that are simulated in the model.

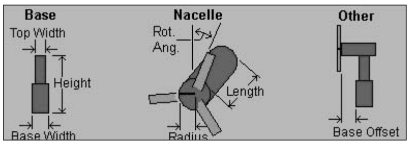


Figure 3. Wind turbine parameters for simulation

At present the blades have been modeled assuming a rest position.

Site background

The site modeled is a proposed wind farm to be located between 7.8 and 12.1 miles southwest of the VOR serving the Sidney Municipal Airport (SNY) at Sidney, Nebraska. The proposed wind farm located at Peetz, Colorado will contain 40 wind turbines. The map in Figure 4 shows the general location of the wind farm and the 40 turbines.

The wind turbines have been modeled using a tower height of 80 meters (262 feet); the towers on which the wind turbines are mounted have been modeled using a diameter of 5 meters (16 feet). Rotors were modeled as a nonmetallic structure of 77 meters (253 feet) in diameter. The diagram in Figure 5 shows the location of the 40 turbines that were modeled relative to the VOR.

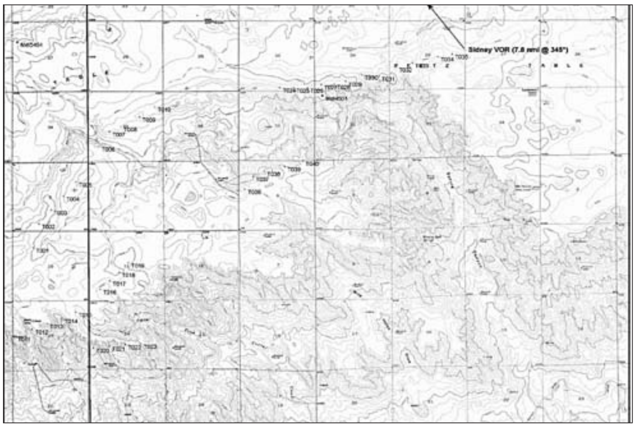


Figure 4. Map showing the location of the windfarm.

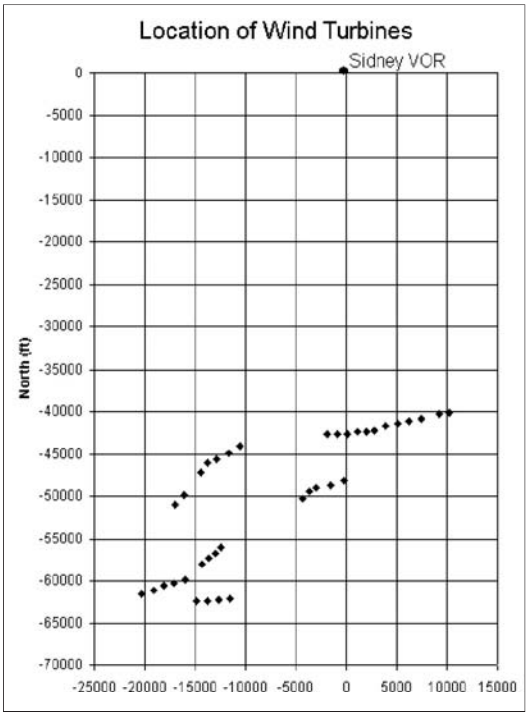


Figure 5. Relative location of wind turbines referenced to the Sidney VOR as used in model

SAMPLE RESULTS

Modeled Flight test results have been obtained for a low elevation orbit of 0.24 degrees (1000 feet AGL at 40 nmi) and also an orbit at an elevation of 1.2 degrees (5000 feet AGL at 40 nmi). The results for the orbital flights are shown in Figure 6 and Figure 7 and are summarized in Table 2. The radials used on the Sidney VOR have also been modeled with the results summarized in Table 3.

Other wind turbine configurations that could minimize their effects on the performance of the Sidney VOR have also been examined. An examination of the present configuration of wind turbines revealed that they have been aligned with an essentially northeast-southwest disposition. This disposition will have a more pronounced effect along the specular directions which is determined by Snell's laws of reflections. Modeling has been conducted to show the performance of the Sidney VOR when the locations of the turbines are scattered in a statistically random manner (see Figure 8). The effect of this random placement within the original area is shown in Figure 9 for low elevation orbital flight (1000 feet elevation at 40 nmi).

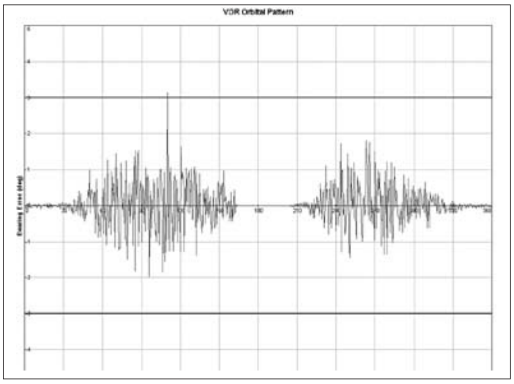


Figure 6. Modeling Results for an Orbital Flight at an Elevation of 0.24 Degrees (1000 ft AGL at 40 nmi).

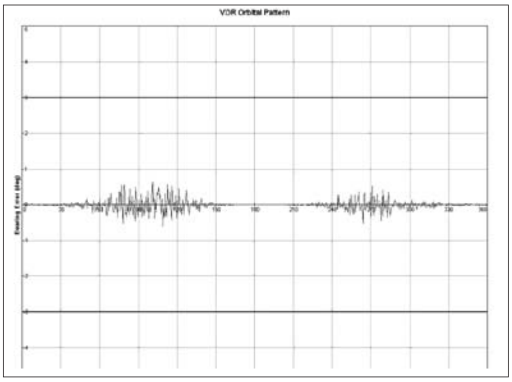


Figure 7. Modeling Results for an Orbital Flight at an Elevation of 1.2 Degrees (5000 ft AGL at 40 nmi).

Table 2. Summary of Modeling Results for Orbital Flight.

Quadrant	0.24 degrees (1000 ft AGL at 40 nmi)		1.2 degrees (5000 ft AGL at 40 nmi)	
	Error (deg/ %)	Bearing (deg)	Error (deg/ %)	Bearing (deg)
1	1.8 / 61%	85.0	0.6 / 18.9%	79.0
2	3.1 / 104.5%	110.0	0.6 / 21.5%	101.0
3	1.8 / 59.9%	263.5	0.5 / 17.4%	264.0
4	1.5 / 50.4%	270.0	0.5 / 17.7%	271.0

Table 3. Summary of Modeling Results for Radial Flight.

Airway	Radial (deg)	Start (nmi)	Stop (nmi)	Elevation (feet MSL)	Maximum (deg / %)	Bearing Error (location nmi)
V6	278	63	0.5	8500	0.92 / 30.5	60.785
V6	78	80	0.5	6000	2.2 / 73.3	79.017
V138	262	81	0.5	7600	1.59 / 52.8	78.295
V169	176	57	0.5	6400	0.11 / 3.6	10.422
V169	322	53	0.5	7000	0.38 / 12.7	46.766
V160	202	59	0.5	8000	0.08 / 2.5	8.869
Runway						
RWY 12	310	10	0.5	6100-4700	0.04 / 1.2	8.526
RWY 30	113	10	0.5	5800-4700	0.45 / 15.0	9.509

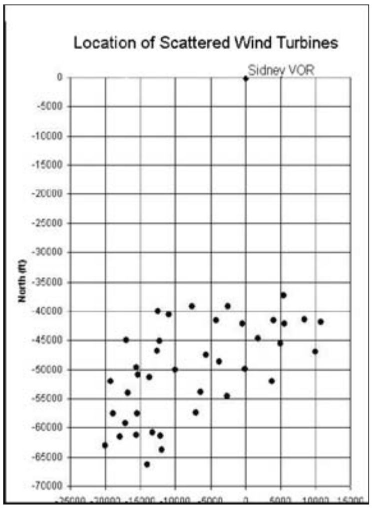


Figure 8. Randomly Located Wind Turbines.

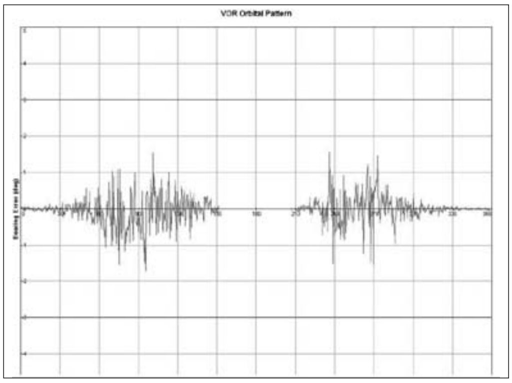


Figure 9. Modeling Results for a low elevation Orbital Flight for Randomly Located Wind Turbines.

Discussion of Results

The results obtained for an orbital flight modeled at an elevation of 0.24 degrees (1000 feet AGL at 40 nmi) does indeed show a situation that produces out-of-tolerance conditions. However, it does not appear likely that the Sidney VOR is used at such a low elevation angle. If indeed the Sidney VOR is used at such a low elevation angle, then the wind turbines will degrade the performance of the VOR system to levels that may be unacceptable.

Another orbital test was modeled at an elevation of 1.2 degrees (5000 feet AGL at 40 nmi) based on the navigation chart for the Sydney VOR. Results indicate that the VOR will perform at a level that may be considered acceptable with a maximum of 21.5 % of VOR performance tolerance limits.

All of the radials and Victor Airways used on the Sidney VOR were modeled. The degradation of the VOR performance for Victor Airway V6 on the 78-degree radial is considered significant, while the performance on Victor Airway V138 is considered slightly significant but well within tolerance limits.

Other radials modeled indicate that the system will operate at acceptable levels. The situation on V6 and V138 only occurs very close to the limit of the VOR range for these airways which is well beyond the nominal 40-nmi navigation changeover point for the airway.

When the wind turbines are randomly located, the results obtained showed a slightly better system performance.

The conclusion reached in this study is that the VOR located at Sidney Municipal Airport, Sidney, Nebraska, should still perform within acceptable levels even in the presence of the proposed windfarm at Peetz, Colorado on most of the radials used on this VOR. While the performance on Victor Airway V6 may be degraded in a significant manner near the edge of its useful range, it is expected that the system will still perform within tolerance limits.

The results obtained for the Peetz, Colorado, modeling task does show that although the VOR performance is not degraded beyond tolerance limits in most of the cases, a wind farm located up to 7 miles away from a VOR still does have noticeable degradation effects on the performance of the VOR.

Considering the height of each turbine and their distances, the elevation angle subtended by the closest turbine to the VOR site is 0.35 degrees. For a large structure like the wind turbine, the siting criterion puts a limit of 1.2 degrees or less on the structure. So, strictly going by the siting criteria, the wind farm located at Peetz Colorado should have a minimal effect on the performance of the VOR at Sidney, Nebraska. However, the Peetz, Colorado model results have shown that such proposed installation should be adequately checked out before any approval is given.

The siting criteria will apply more to just a single structure of this type. To buttress this point, a single turbine was modeled at the center of the proposed wind farm and the result is as shown in Figure 10. This result does indicate that the effect of this one turbine is in fact minimal. However, when compared to the result obtained for 40 turbines, it does show that a cluster of these turbines can not use the same siting criterion that is used for the single turbine.

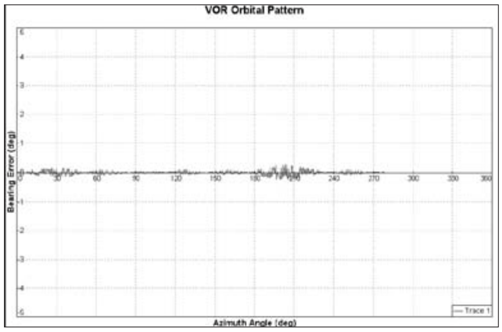


Figure 10. Modeling result for a single wind turbine

CONCLUSIONS

Modeling analysis has shown that wind turbines installed in clusters known as windfarms have significant effects VOR performance even when these wind farms are located several miles away from the VOR. The current VOR siting criteria does not provide any criteria to evaluate such clusters of wind turbines sited near a VOR.

This study is based on a wind farm with 40 turbines. As the popularity of the wind turbine increases the tendency is for a greater number of turbines to be installed on one wind farm. In fact there are wind farms in existence that have more than 400 wind turbines. As this number grows, the potential for the large windfarm to affect a navigation system also increases.

RECOMMENDATION

Further studies must be done to produce comprehensive siting criteria for the development of wind farms when they are located within line of sight of the VOR. These studies must also be extended to other navigation aids especially those that have high susceptibility to multipath.

REFERENCES

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3. M.M. Butler and D. A. Johnson, "Feasibility of Mitigating the Effects of Windfarms on Primary Radar," ETSU W/14/00623/REP, DTI PUB URN No. 03/976, Alenia Marconi Systems Limited, Published 2003.