IMPACT OF RIVIERA WIND FARM ON TACTICAL AIR NAVIGATION (TACAN) BEACON AT NAVAL AIR STATION KINGSVILLE

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1. Abbreviations

AGL	Above Ground Level
ATC	Air Traffic Control
BRA	Building Restricted Area
CAA	Civil Aviation Authority
CAD	Computer Aided Design
DME	Distance Measuring Equipment
DOD	Department of Defense
DOT	Department of Transportation
FAA	Federal Aviation Administration
IAP	Instrument Approach Procedure
ICAO	International Civil Aviation Organization
I/N	Interference to Noise ratio
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
LOS	Line of Sight
NAS	Naval Air Station
Navaid	Navigational Aid
NTIA	National Telecommunications and Information Administration
PSR	Primary surveillance radar
RF	Radio Frequency
RWY	Runway
SSV	Standard Service Volume
TACAN	Tactical Air Navigation
Tx/Rx	Transmitter/ Receiver
USGS	US Geological Survey
VOR	VHF Omnidirectional Radio
VORTAC	VHF Omnidirectional Radio / Tactical Air Navigation
WT	Wind Turbine
WTG	Wind Turbine Generator

2. Introduction

2.1 Overview of Tactical Air Navigation (TACAN)

TACAN, or Tactical Air Navigation, is a polar coordinate type radio air-navigation system that provides distance and bearing information to an aircrew [1]; it operates in the 960 to 1215 MHz frequency band. The distance and bearing information provided by the system appears to the aircrew as two dials, one displaying the slant-range distance from a select ground-level beacon to the aircraft and the other displaying the direction of the beacon in regards to the aircraft's flight direction. The aircrew uses this information when flying towards the beacon or for establishing geographic location with respect to the beacon.

TACAN works on radar-ranging techniques. The TACAN ground station receives and decodes the RF pulse emitted by an airborne transponder and provides a frequency-modulated reply after a 50-microsecond delay. The frequency-modulated element allows the airborne equipment to determine bearing information, while the amount of time elapsed between the sending of the interrogation and the receipt of a reply is used to calculate distance.

TACAN is a combination of civilian VHF omnidirectional radio (VOR) and distance measuring equipment (DME) systems; the directional element of TACAN is three to nine times more accurate than the civilian VOR system. While the VOR is used to establish bearing, DME is used to establish the distance to a beacon. When a VOR and a TACAN are co-mounted, the installation is called a VORTAC; in this case, the DME system of the TACAN is available to both civil and military users, while the bearing system is not shared.

First implemented in the 1950's, the TACAN system has been in use for over half a century, with civilian VOR/DME systems in use for longer. With the introduction of satellite-based navigation systems like GPS within the past two decades, plans to switch to the satellite-based systems as the primary navigation methods have been set in motion. The 2008 Federal Radionavigation Plan [2] states that efforts are underway to phase out VOR, DME, and TACAN systems within the upcoming decade, maintaining service until all aircraft receive the upgrades to satellite navigation while maintaining a backup network for secondary navigation needs. Although the TACAN beacon network may be thinned and relieved of primary navigation duty, a core network will remain in operation to serve as a safety measure if primary navigation aid(s) fail.

2.2 Objective

The goal of this study is to determine whether the proposed Riviera Wind Farm will cause RF interference in TACAN communication between the NAS Kingsville TACAN and aircraft interrogating it and to develop wind turbine exclusion zones based upon operational and siting criteria.

The four areas of focus are:

- TACAN siting criteria
- Potential for LOS blockage
- Fresnel zone clearance
- Determination of potential exclusion zones for wind turbines

2.3 Executive Summary

A minimum distance between a wind turbine and a TACAN beacon is defined by FAA Order 6820.10, which prohibits a metallic structure from subtending an angle greater than 1.2 degrees with respect to the TACAN beacon; thus the specified model wind turbine should not be within 3.15 nautical miles of the TACAN beacon. [Refer to Figure 22]

Exclusion zones for wind turbines may be set up based upon requirements set forth by standard service volumes for navigational aids and minimum safe altitudes within 25 nautical miles of NAS Kingsville. For the minimum safe altitudes mandated around NAS Kingsville for aircraft 25 nmi from the TACAN beacon at 2,100 ft AGL, 1,900 ft AGL, and 1,700 ft AGL, wind turbines should be no closer than 7.6 nmi, 8.5 nmi, and 9.8 nmi, respectively. For the lower bound of the terminal standard service volume (aircraft at 1,000 ft AGL, 25 nmi from beacon) to be unaffected, wind turbines should not be closer than 16.8 nmi.

Based upon the minimum safe altitudes set forth for aircraft operating within 25 nautical miles of the TACAN antenna, a sectorized exclusion zone featuring a combination of the 7.6 nmi, 8.5 nmi, and 9.8 nmi exclusion zones is viable. Each of the three sectors around NAS Kingsville would thus have a different minimum distance. [Refer to Figures 26 & 27]

Ultimately, Riviera wind farm should not significantly impact TACAN operation at NAS Kingsville, though the determined exclusion zones should be considered for future wind farm projects that may see wind turbines being brought closer to the TACAN beacon. The selection of the exclusion zone radius is dependent on the day-to-day operations and safety requirements necessary at the airport in question. While the radius defined by FAA Order 6820.10 is a minimum, the radii based on minimum safe altitudes are also important.

3. Cartographic Data for Computations

ATDI's RF network modeling platform, HTZ Warfare, is a comprehensive RF communications software application for civil and military networks operating from 10 kHz up to 450 GHz. HTZ Warfare offers a graphical GIS map interface for a local single user or networked planning teams. HTZ Warfare offers features that can allow it to be a specialist toolbox for network design, optimization, and validation.

HTZ Warfare uses digital terrain and clutter information from various sources including NASA SRTM, USGS NED and SDTS to define the modeling environment. The GeoData from these sources are converted to raster matrices in ATDI's proprietary format. This format can be defined in the following way:

- **Digital Terrain Model (.GEO):** Contains bald earth terrain altitudes.
  For this study, ATDI prepared a UTM (Universal Transverse Mercator) projected terrain tile to serve as the base workspace grid for modeling. The UTM coordinate system is a grid-based method of specifying locations on the surface of the Earth that is a practical application of a 2-dimensional Cartesian coordinate system.

- **Clutter Layer (.SOL):** Typically contains a 2D description of the above ground morphological conditions of a given environment. This is described as a series of values on a grid that refers to 'clutter codes' that are freely reinterpreted with propagation characteristics inside HTZ Warfare. For this study, the clutter file along with a code for wind turbine locations and its height were used to describe effective obstructions within the terrain.

- **Image Layer (.RIM/.PAL):** Contains the color code and imagery values that constitute a reference map whether it is a digitized paper map, satellite photo or aerial photo. For this study, ATDI created both USGS 1:24K Scale Digital Raster Graphics (DRG) map and 1 meter resolution USGS National Agriculture Imagery Program (NAIP). A DRG is a scanned image of a U.S. Geological Survey standard series topographic map, including all map collar information. The image inside the map neatline is georeferenced to the surface of the earth and fit to the UTM projection. The horizontal positional accuracy and datum of the DRG matches the accuracy and datum of the source map. NAIP is aerial imagery acquired during the agricultural growing seasons in the continental U.S.

Each of the above matrices are projected in a metric projection to allow HTZ Warfare to accurately perform calculations. The clutter and imagery matrices are overlaid on the terrain matrix with each layer containing distinct information relevant to calculating the path loss between any points on the map.

Below is an example of how the GeoData is loaded into HTZ Warfare after it is prepared in ATDI format:

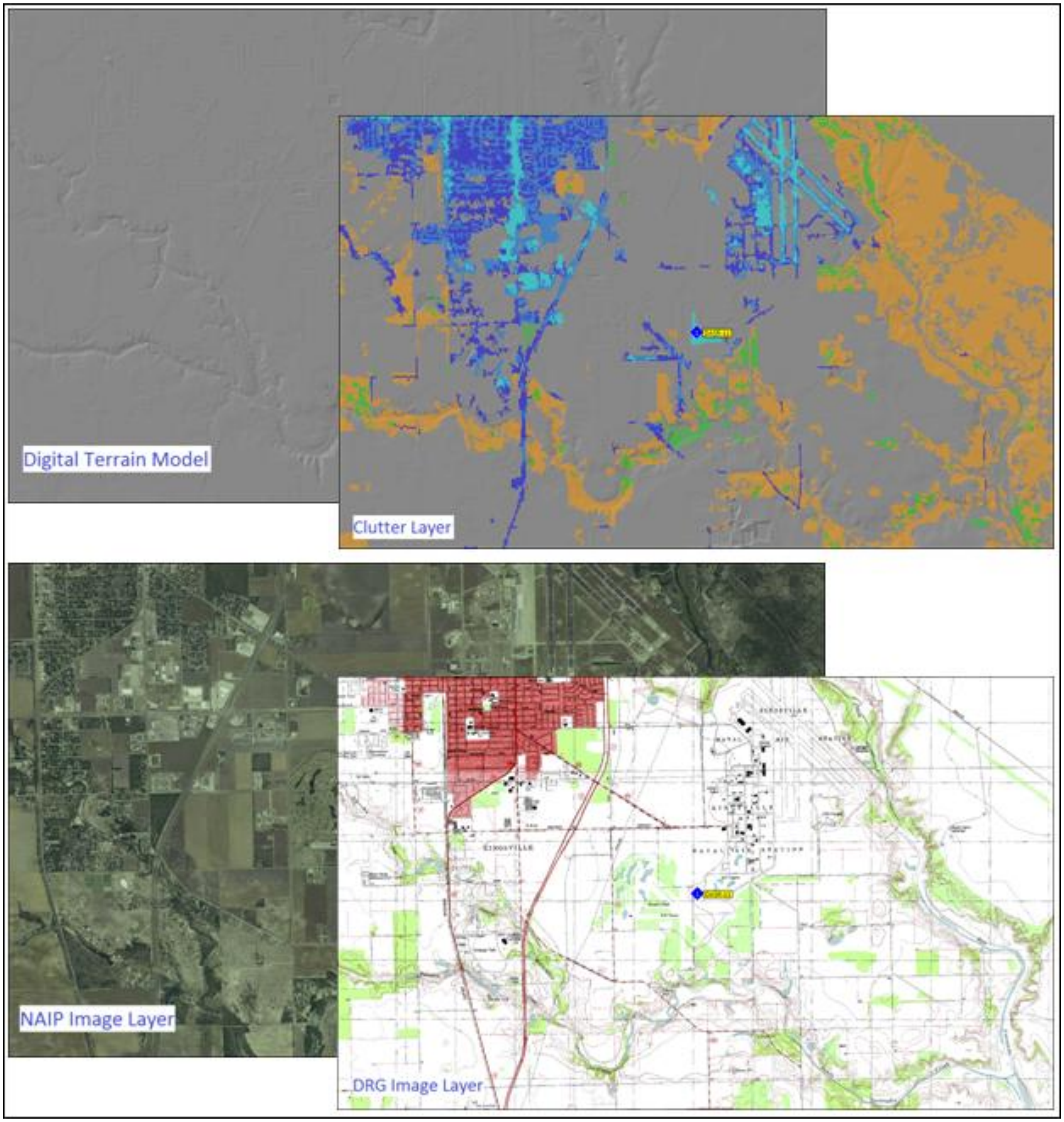

Figure 1: Cartography in HTZ Warfare

4. TACAN Siting Criteria

This section of the report explores the siting criteria for navigational aid (navaid) antennas, especially TACAN, established by several different national and international entities. The aim is to determine whether the proposed wind turbines of Riviera Wind Farm would be located within a restricted area or would impinge on protected airspace.

4.1 Wind Energy and Aviation Interests: Interim Guidelines

The 'Wind Energy and Aviation Interests: Interim Guidelines' [3] report is unique among reports pertaining to wind turbines and their potential negative effects for air traffic and air navigation. It was authored by the Wind Energy, Defence, & Civil Aviation Interests Working Group; this group has members with aviation-related priorities (British Ministry of Defence and the UK's Civil Aviation Authority) and members with wind energy-related priorities (UK Department of Trade and Industry Sustainable Energy Programme and the British Wind Energy Association). The document features a diagram that illustrates the height of wind turbines with respect to low flying and tactical training areas, shown below.

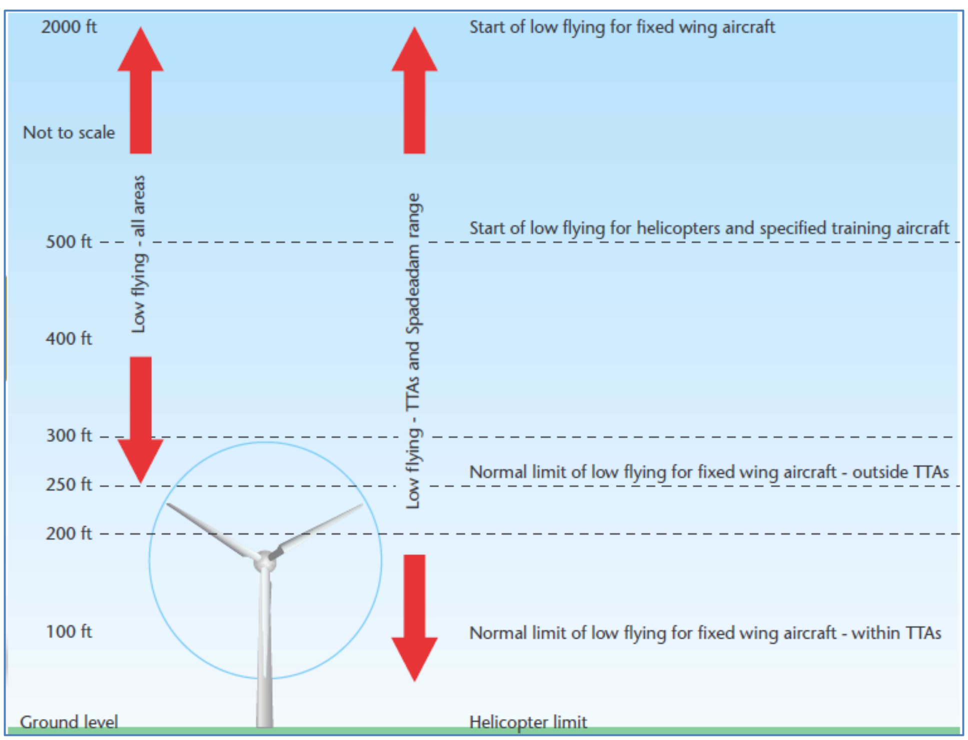

Figure 2: Comparison of wind turbine height with low flying zones

Though low flying and tactical training area boundaries vary from country to country, typically near airports aircraft must navigate safely at low altitudes. Furthermore, a Naval Air Station like Kingsville that focuses on pilot training which conducts low-altitude training flights mandates interference-free low-altitude zones. The diagram above clearly portrays the height of an average wind turbine and how it may impinge on tactical and low flying zones.

4.2 CAP670: Air Traffic Services Safety Requirements

The UK Civil Aviation Authority (CAA) has had a head start on researching the adverse effects that wind turbines have on air traffic control systems and navigational aids. This is due to the smaller landmass that is the UK (often limiting the distance between aviation navigational equipment and wind turbines) and a richer early history of wind energy development. Two recent CAA documents are pertinent to this TACAN study: CAP 764 [4] and CAP 670 [5]. CAP 764 (most recent release May 2010) is dedicated solely to airspace-WTG policies and guidelines. It is more useful for radar considerations and refers the reader to CAP 670 for navigational aid inquiries. CAP 670 is entitled 'Air Traffic Services Safety Requirements' and features a section dedicated to the airspace-WTG interference question. Even with a recent release in October 2010, the document still states that "further work is being undertaken to establish the extent, likelihood, and severity of the problem and until further information is available, issues concerning wind turbines and VHF communications should be dealt with on a case by case basis," thus offering no recipe approach to the interference issue.

CAP 670 provides examples of physical protection frames, or protected areas, where structures should not be built. Though the report does not directly address the TACAN system, using the more stringent guidelines of the VOR and DME protection frames is helpful because TACAN is a combined and more accurate version of the two. For VOR, "at ground level a circle of 230 meters radius from the site centre with a further slope at 2% (1:50) out to 900 meters radially from the site centre," is the protection zone. For DME, "the foregoing VOR constraints where co-located with a VOR otherwise a 2% (1:50) slope surface originating at the site ground level extending 300 meters radially."

Given these descriptions, it is evident that the Riviera Wind Farm, with the nearest turbine to the TACAN antenna being approximately 18,800 meters away, does not fall within the ground nor the airspace protection zones for neither the VOR nor the DME specifications. Ignoring the 900 meter and 300 meter outer bounds of the protection frames, respectively, and extending the 2% slope as far as the Riviera Wind Farm, it is evident that wind turbines do not impinge on this expanded inverted conical protection frame either. By the point that the wind turbine nearest the TACAN beacon is reached, the height of the inverted cone would be approximately 350 meters, almost triple the height of the 125 meter wind turbines.

4.3 ICAO EUR DOC 015: European Guidance Material on Managing BRAs

Much like CAP 670 in the previous section and the FAA Order discussed in the following section, ICAO EUR DOC 015 [6] defines a Building Restricted Area (BRA). The BRA is "defined as a volume where buildings have the potential to cause unacceptable interference to the signal-in-space in the service volume of CNS (Communication, Navigation, and Surveillance) facilities for AWO (All Weather Operations)." It provides worst case protection for navigational aids. The figure below shows the side profile of the BRA with VOR/DME-specific values for the variables located in the table below.

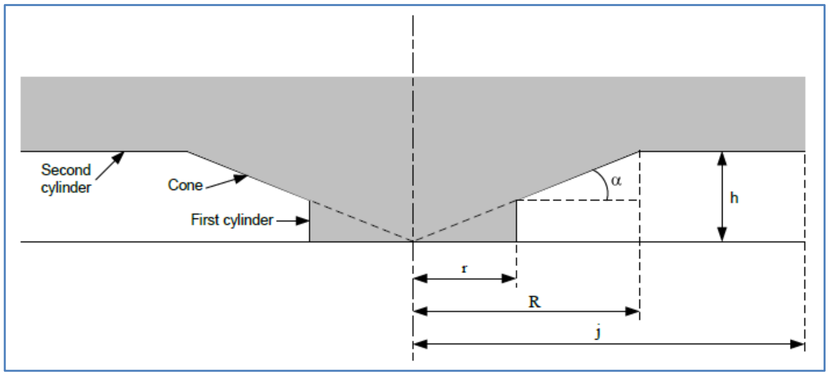

Figure 3: ICAO EUR 015 definition of building restricted area

Table 1: ICAO EUR 015 BRA parameter values

Type of navigation facilities	*Radius (r – Cylinder) (m)*	*Alpha (a – cone) (°)*	*Radius (R- Cone) (m)*	*Radius (j – Cylinder) (m) Wind turbine(s) only*	*Height of cylinder j (h -height) (m) Wind turbine(s) only*	*Origin of cone and axis of cylinders*
DME N	300	1.0	3000	N/A	N/A	Base of antenna at ground level
VOR	600	1.0	3000	15000	52	Centre of antenna system at ground level

Again, as was the case for CAP 670, TACAN is not directly mentioned in this document, but given the fact that it is a combination of the VOR and DME systems (albeit more precise with regards to direction), a combination of the parameters for VOR and DME are used in this analysis. It is important to note that there are parameters for the BRA that are to be used only when nearby wind turbines are being studied. While the regular radius (R) of the cone is limited to 3 kilometers for both DME and VOR, once turbines are present, a second much wider cylinder at a height of 52 meters above ground level is added for further protection. This cylinder, though, only extends to 15 kilometers from the navaid antenna; the Riviera Wind Farm is to be located between 10 nmi (~18.5 km) and 12.5 nmi (~23.2 km) away from the TACAN antenna. If the wind turbines were to be within 15 kilometers of the antenna, their height of 125 meters AGL would mean that more than one half of the wind turbine would be located in the BRA.

However, the document refers to an appendix specifically designed for the assessment of wind turbines and navigational facilities, even though the BRA defined “should provide sufficient protection.” The appendix relates the difficulties common to wind turbine analysis: amount of error is dependent on orientation of turbine and wind speed and direction; worst case error is a summation of errors caused by individual turbines, again subject to many variables; the farther an airborne receiver is from a navaid antenna, the larger the error tends to be. Finally, it states that, “it is unlikely that the worst case errors can be confirmed by flight inspection due to the factors listed.”

4.4 FAA Order 6820.10: VOR, VOR-DME, and VORTAC Siting Criteria

FAA Order 6820.10 [7], entitled ‘VOR, VOR/DME, and VORTAC Siting Criteria’, provides guidance for the siting of navaids in the FAA’s National Airspace System. The order is mainly designed for new installations, though “it also provides information which may be used to evaluate the effect that physical changes proposed in the area of a site may be expected to have on the performance of existing navigational aids” [FAA Order 6820.10].

Chapter 4, Paragraph 17, Part (e) of Order 6820.10 states that, “no structures should be permitted within 1000 feet of the antenna… All structures that are partly or entirely metallic shall subtend vertical angles of 1.2 degrees or less, measured from ground elevation at the antenna site.”

A quick worst-case-scenario calculation is performed to determine whether the wind turbines of Riviera Wind Farm would meet the above mentioned siting criterion. For this worst-case scenario, both the TACAN antenna and the wind turbine are assumed to be at 0 meters AGL. Flat earth with no obstructions is also assumed. The wind turbine nearest the TACAN antenna is chosen for this scenario as it will provide the greatest subtended angle.

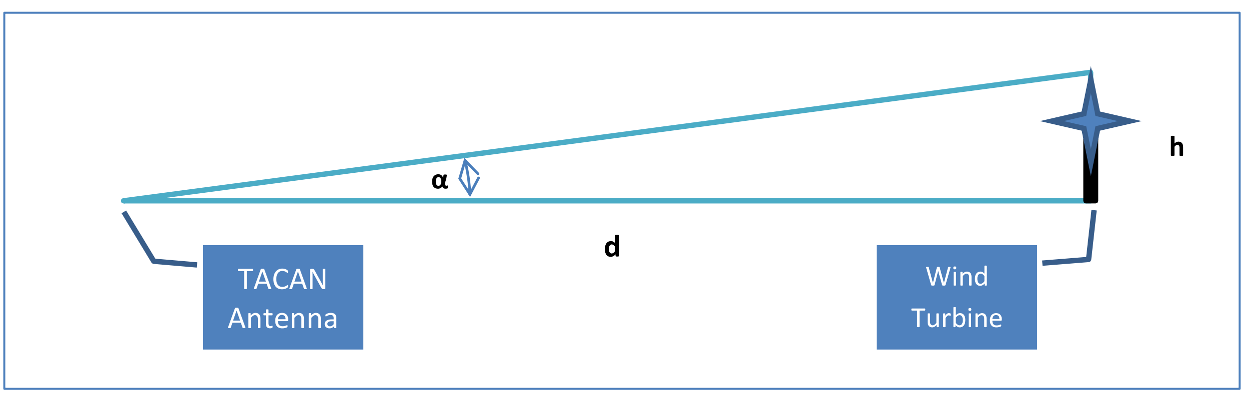

Figure 4: Angle subtended by WTG during worst-case scenario

The approximate distance between the TACAN installation and the nearest wind turbine is 18,800 meters. The height of the Vestas V90-1.8MW wind turbines to be erected is 125 meters. Given these two parameters, we solve for the angle subtended by one such wind turbine in a worst-case scenario:

$$\propto = \tan^{-1}\frac{h}{d} = \tan^{-1}\frac{125\ m}{18{,}800\ m} = 0.38° \quad [1]$$

Thus, even in a worst-case scenario, a wind turbine from the Riviera Wind Farm will not subtend an angle greater than 1.2 degrees, meeting this requirement of FAA Order 6820.10.

The order goes on to define standard service volumes (SSVs) for navigational aids of Terminal, Low Altitude, and High Altitude classes. The service volume of a navaid is defined as a volume of adequate signal coverage and frequency protection from other navaids on the same frequency, as defined in the *Instrument Procedures Handbook,* published by the FAA. Order 6820.10 states that outside the service volume, reliable service may not be available. Thus, a review of the TACAN service volume is undertaken to determine whether or not the Riviera Wind Farm may impinge upon it, potentially creating regions of diminished signal strength.

The TACAN located at NAS Kingsville can serve all three principle service volumes. These service volumes are listed in the table below, obtained from the FAA's *Aeronautical Information Manual* [8] but also available in other documents (i.e. FAA Order 6820.10 and others).

Table 2: VOR/DME/TACAN Standard Service Volumes

SSV Class	Altitude & Range Boundaries
T (Terminal)	From 1,000 ft AGL up to and including 12,000 ft AGL at radial distances out to 25 nmi.
L (Low Altitude)	From 1,000 ft AGL up to and including 18,000 ft AGL at radial distances out to 40 nmi.
H (High Altitude)	From 1,000 ft AGL up to and including 14,500 ft AGL at radial distances out to 40 nmi. From 14,500 ft AGL up to and including 60,000 ft at radial distances out to 100 nmi. From 18,000 ft AFL up to and including 45,000 ft AGL at radial distances out to 130 nmi.

The upper bounds of these service volumes are of little interest in this matter because the majority of the energy emitted by the TACAN antenna is between 5 degrees and 40 degrees above the horizon, a volume that the wind turbines do not infringe upon. Of greater interest are the lower bounds (located at the ground position of the TACAN antenna and extending to 1,000 ft AGL at a certain distance from the TACAN) of these three standard service volumes, defined by the two graphs below. The Low Altitude and High Altitude SSVs share the same lower bounds while the Terminal SSV has a unique lower bound.

It is of interest whether the proposed wind turbines infringe upon the three SSVs, as the NAS Kingsville TACAN may be used in all three scenarios. The turbines are to be located approximately between 10 nautical miles and 12.5 nautical miles from the TACAN antenna and are 410 feet (125 m) high. The height and depth of the proposed Riviera Wind Farm is added to the two figures below for a graphical representation of whether the turbines infringe on the SSVs and if so, to what extent.

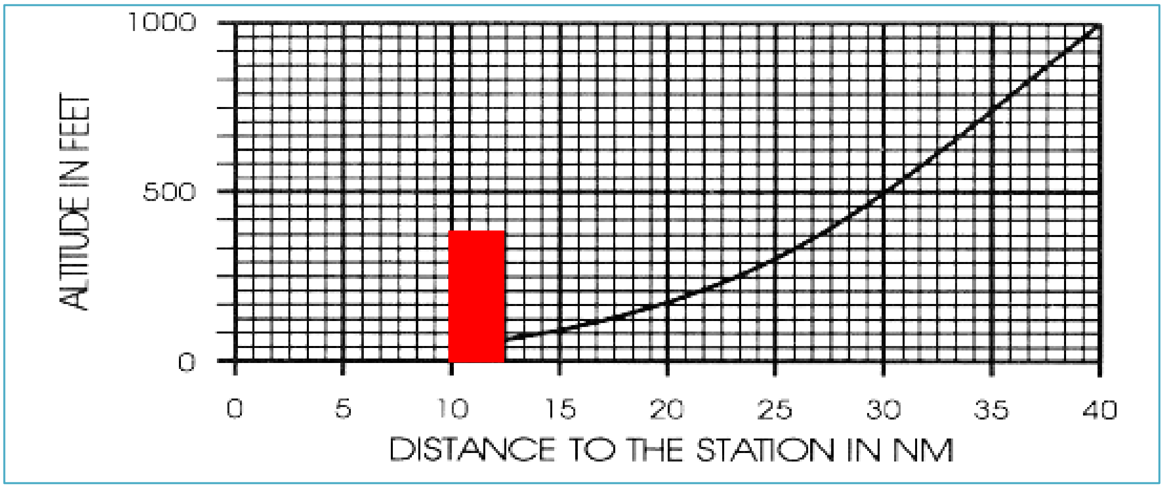

Figure 5: Wind turbines with respect to lower bounds of L & H SSVs

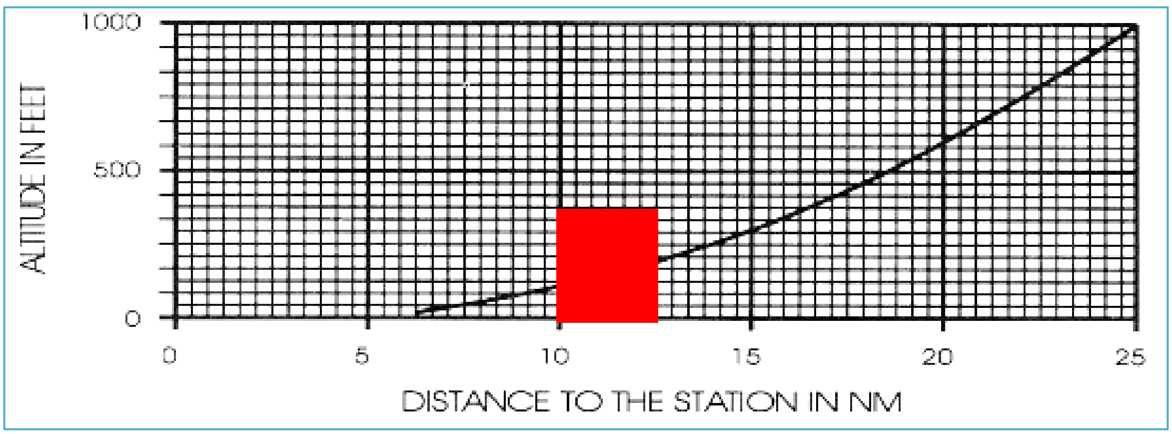

Figure 6: Wind turbines with respect to lower bound of Terminal SSV

The proposed wind turbines infringe upon the lower bounds of all three of the standard service volumes and may potentially cast shadows of little to no signal strength behind them. TACAN system performance may thus be degraded at the lower bounds of the standard service volumes.

5. Possible Interference Effects on TACAN Communication

The potential interference effects to the TACAN system because of the installation of wind turbines are:

- Shadowing
- Scattered multipath
- Multipath within Fresnel zones

The interference effects are described in the following sections, followed by a detailed analysis of the Kingsville scenario.

5.1 Shadowing

As is the case with primary surveillance radar (PSR), a wind turbine generator is a large metallic structure that has the potential to block electromagnetic waves. The waves will hit the object and be scattered in all directions, including directly back at the sending antenna. The result is an area of potentially weakened signal behind the wind turbine. The two figures below, obtained from a Eurocontrol document [9] portray the horizontal and vertical shadow regions created by a single wind turbine; understandably, a wind farm will potentially create a much greater horizontal shadow, while the vertical shadow will stay roughly the same given uniform turbine heights.

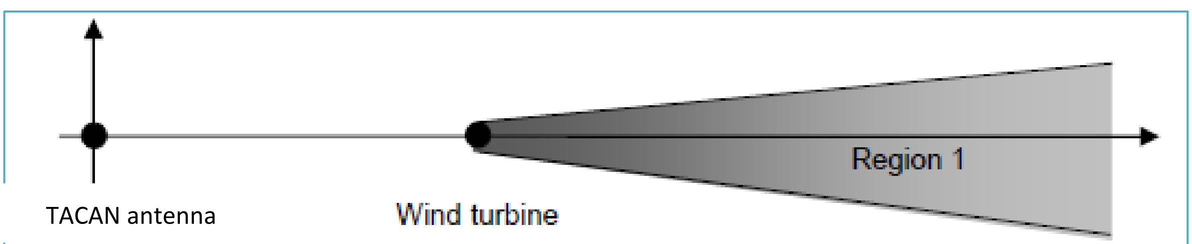

Figure 7: Horizontal extent of shadow region

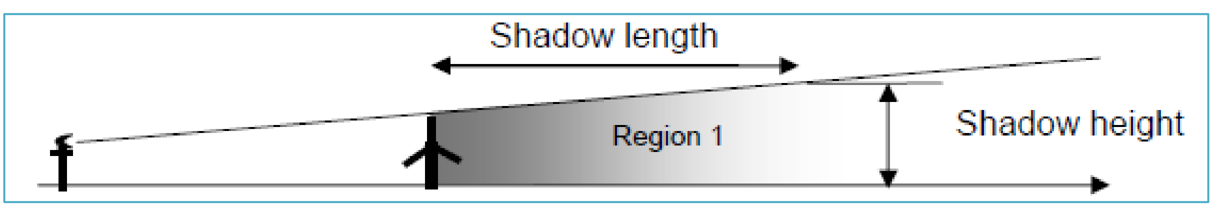

Figure 8: Vertical extent of shadow region

Such shadow regions of diminished signal strength may prevent a signal from reaching its destination or may lower the power of the signal to a level such that the receiver does not detect its presence. The shadow region affects both inbound and outbound signals for a TACAN beacon; that is, a signal that is to be received by the TACAN antenna is affected as much as a signal that is being transmitted by the antenna, though the extent of the shadow length and height might vary. The extent of the shadow region is directly correlated with dimensions of clutter in the vicinity of the TACAN antenna. A taller structure will cast a greater shadow.

Shadow regions and their respective heights are of interest in a TACAN interference study because a TACAN antenna may have an effective operating range of up to 200 nautical miles. To be effective at such a distance, the antenna pattern must have high gain at vertical angles near and slightly above horizontal; a typical TACAN antenna pattern will have 60% or more of its maximum gain positioned between 5 and 40 degrees above horizontal. This allows communication between the antenna and distant interrogating aircraft that may potentially only have an altitude of several thousand feet above ground level (AGL).

The Department of Defense Interface Standard for the TACAN signal (MIL-STD-291C) [10] states that "at vertical angles from the horizon to 6 degrees above the horizon the root means square (r.m.s.) sum of the second through the sixth harmonics of the 15 Hz modulation component of the radiated signal shall not exceed 20 percent. The r.ms. sum of the harmonics of the 135 Hz modulation component of the radiated signal shall not exceed 15 percent. The amplitude of modulation components radiated at frequencies of 105 Hz, 120 Hz, 150 Hz, and 165 Hz individually shall not exceed 15 percent nor shall the r.m.s. sum of these components exceed 20 percent."

5.2 Scattered Multipath

When an electromagnetic signal is incident upon a wind turbine (be it the tower, the blades, or the nacelle) its energy is scattered dependent on the angle of incidence. Since the nacelle and blades of a wind turbine are typically not stationary, it is not likely that the angle at which the signal is reflected stays the same over time. Thus, a wind turbine is an unpredictable scatterer.

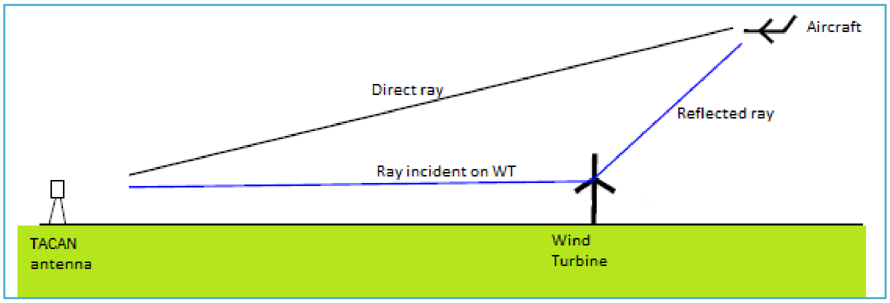

Figure 9: Scattered multipath

It is possible for a ray to be reflected directly at an aircraft, where the reflected ray meets with the direct ray. Conversely, it is possible for a signal sent from the aircraft that is in communication with the TACAN beacon to reflect off a wind turbine towards the TACAN antenna, meeting there with the direct signal. If the timing of the arrival of the two signals is negligible (which it might be given a long distance of communication and a low angle of inclination for the direct ray), the energies of the two rays may interfere destructively, essentially creating a signal of no energy. Though unlikely, such a scenario is possible, though Transponder Dead Time and Echo Suppression Dead Time processing algorithms are most likely in use, eliminating unwanted reflected signals.

5.3 Multipath within Fresnel zones

The most dangerous form of multipath is the type that occurs when the electromagnetic energy within the second Fresnel zone of a direct signal is incident upon a structure and reflected towards a receiver, arriving there and destructively interfering with the direct signal. The following paragraph from the *Practical Radio Engineering and Telemetry for Industry* [11] book describes Fresnel zones:

> It has been shown that the energy received under free space conditions is the resultant of an infinite number of coherent waves all arriving at the receiver via different paths. All the paths arriving at the receiver antenna dipole, and which are within one half wavelength of the illusory direct path, will be added algebraically. They will contribute their energy to the received signal. The other paths (which may have been more widely refracted or reflected) and which thus arrive from one half to a full wavelength later, will combine to subtract energy from the previously received signal. This adding and subtracting continues with additional wavelength delays. Therefore, the received wave front now begins to look a little like a banana – with many layers of skin arranged like concentric tubes. Thus, the first and third and fifth tubes will all add to the signal and make it stronger whilst the second and fourth and sixth tubes will reduce the signal and sometimes even cancel it out altogether. The so-called tubes are really elliptical zones around the direct path line and they are called Fresnel Zones, after the man who discovered a similar behavior in light waves.

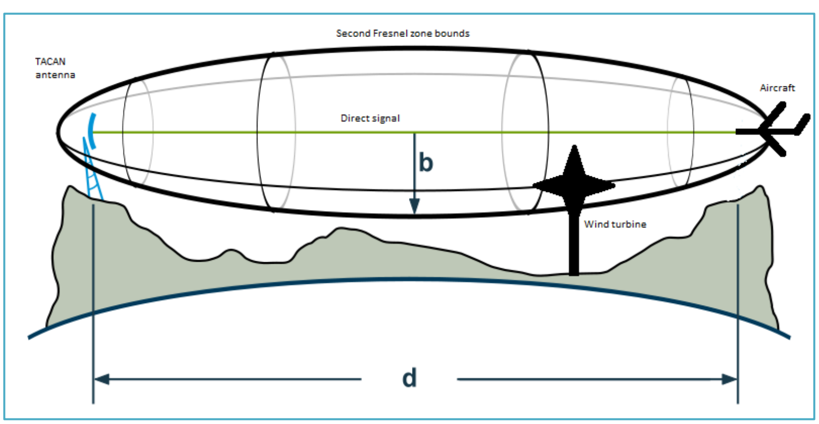

Figure 10: Wind turbine impeding upon Fresnel zone

The figure above and the figure below show two depictions of Fresnel zones. In the figure above, a hypothetical wind turbine is within the second Fresnel zone of a direct signal. In such a case, the energy reflected by the wind turbine may combine destructively at the receiver, creating a null. A null occurs when the total received energy is zero, leading to the loss of communication. This is a dangerous possibility that may leave a pilot without distance and bearing information. The figure below portrays Fresnel zone clearance with regards to terrain; elevated terrain may also lead to reflections within the second Fresnel zone, producing a weakened, if not null, signal.

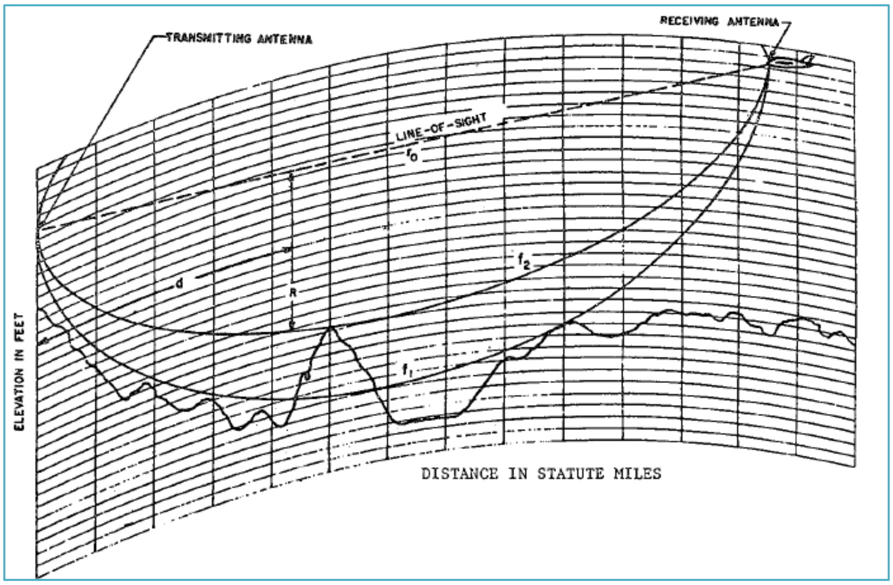

Figure 11: Fresnel zone interference according to FAA Order 6820.10

Since the paths beyond the second Fresnel zone do not have a significant impact on the overall power of the signal received, they are of negligible importance. Thus, our focus is on the first and second Fresnel zones. Ideally, the second Fresnel zone should be completely clear of obstacles. FAA Order 6820.10 is somewhat lenient, stating that, “the first Fresnel zone should be clear of obstructing objects in order to minimize fading.” Thus, Order 6820.10 focuses more on the positive summation of the energy carried within the first Fresnel zone of a direct signal and not directly on the dangers of energy within the second Fresnel zone. If all energy within the first Fresnel zone is received, it should be enough to outweigh any energy reflected negatively within the second Fresnel zone.

6. Shadow Height and Fresnel Zone Clearance Analysis

6.1 Shadow Height Calculation

Basic shadow height calculations were performed in the siting section based on the literature that was referred to. A more accurate determination of shadow heights that takes into account the curvature of the Earth is required though, especially when investigating the effects that the wind turbines might have on landing procedures at NAS Kingsville. The procedure published by the European Organisation for the Safety of Air Navigation in the document “Guidelines on How to Assess the Potential Impact of Wind Turbines on Surveillance Sensors” [9] for the determination of shadow heights behind wind turbines is adopted here. The figure and equations below are both modified versions of those found in the European Organisation for the Safety of Air Navigation document. All heights above the effective radius of the Earth are assumed to be above mean sea level. The average ground level in the Kingsville area is around 10 meters (approximately 33 feet) above mean sea level.

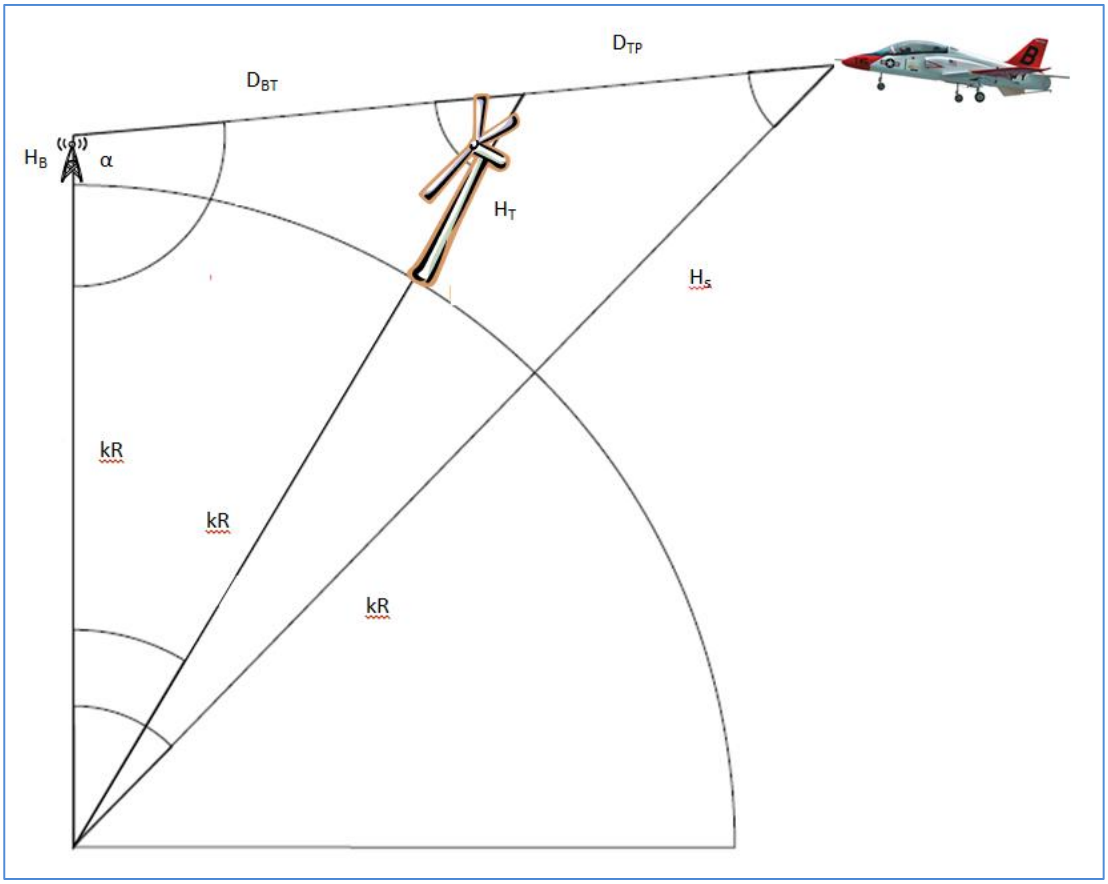

Figure 12: Shadow height diagram

where:

H_B is the height of the TACAN beacon (24 m)
H_T is the height of a wind turbine (135 m)
H_S is the height of the shadow cast by the wind turbine (varies with distance)
k is the average refractive index of the Earth (4/3)
R is the radius of the Earth (6371 km)
D_{BT} is the distance from the TACAN beacon to the wind turbine (varies)
D_{TP} is the distance from the wind turbine to an airplane (varies)
α is the angle between the vertical axis of the TACAN beacon and an airplane

As we are interested in the worst case scenario, the turbine closest to the TACAN beacon (~10 nmi), and thus the one most likely to cast the tallest shadow, is considered in this calculation. First, a calculation of the angle α to determine the angle between the vertical axis of the TACAN beacon (from the beacon's highest point) to the top of the wind turbine:

$$\alpha = \cos^{-1}\frac{{D_{BT}}^2+(H_B+kR)^2-(H_T+kR)^2}{2(D_{BT})(H_B+kR)} \qquad [2]$$

$$\alpha = \cos^{-1}(-4.43 * 10^{-3}) = 90.254° \qquad [3]$$

The angle between the TACAN beacon's vertical axis and the top of the nearest wind turbine is 90.254°. Thus, when at the top of the TACAN beacon, the top of the nearest wind turbine is 0.254° above horizontal with respect to the antenna.

Next a formula for the calculation of shadow height is derived from the law of cosines ($a^2 = b^2 + c^2 - 2*b*c*\cos(\alpha)$).

$$(kR+H_S)^2 = (kR+H_B)^2 + (D_{BT}+D_{TP})^2 - 2(kR+H_B)(D_{BT}+D_{TP})\cos\alpha \qquad [4]$$

$$H_S = \sqrt{(kR+H_B)^2 + (D_{BT}+D_{TP})^2 - 2(kR+H_B)(D_{BT}+D_{TP})\cos\alpha} - kR \qquad [5]$$

The area around NAS Kingsville is quite flat with peak elevations averaging between 15 and 20 meters above mean sea level. Using the above equation, potential turbine shadow heights are calculated.

Table 3: Turbine shadow heights

Distance beacon to aircraft (nmi)	Turbine shadow height (m)	Turbine shadow height (ft)
10	128	420
20	271	890
30	455	1492
40	679	2226
50	943	3093
60	1247	4092
70	1592	5224
80	1977	6487
90	2403	7883
100	2869	9412
110	3375	11072
120	3921	12865
130	4508	14790
140	5135	16847
150	5802	19037
160	6510	21358
170	7258	23812
180	8046	26397
190	8874	29115
200	9743	31964

TACAN beacons have a service range of up to 200 nautical miles; the NAS Kingsville TACAN has a range of 130 nautical miles. At this range, aircraft below 15,000 feet altitude are likely not to be able to communicate with the beacon.

6.2 Fresnel Zone Clearance Analysis

Due to the dangers of the power contained within the second Fresnel zone of an electromagnetic signal, it is important to consider the clearance necessary between a direct ray and a possible reflector to minimize the potential for the creation of a null. This portion of the analysis evaluates the extra amount of clearance above the already calculated shadow zone that is necessary for the complete first Fresnel zone of a direct signal not to impact on a wind turbine, thus allowing for the maximum amount of energy to reach the receiver. The figure below shows the height comparison between shadow height and the flight altitude required for Fresnel zone clearance without taking Earth bulge into account (though Earth bulge is taken into account in the equations that follow).

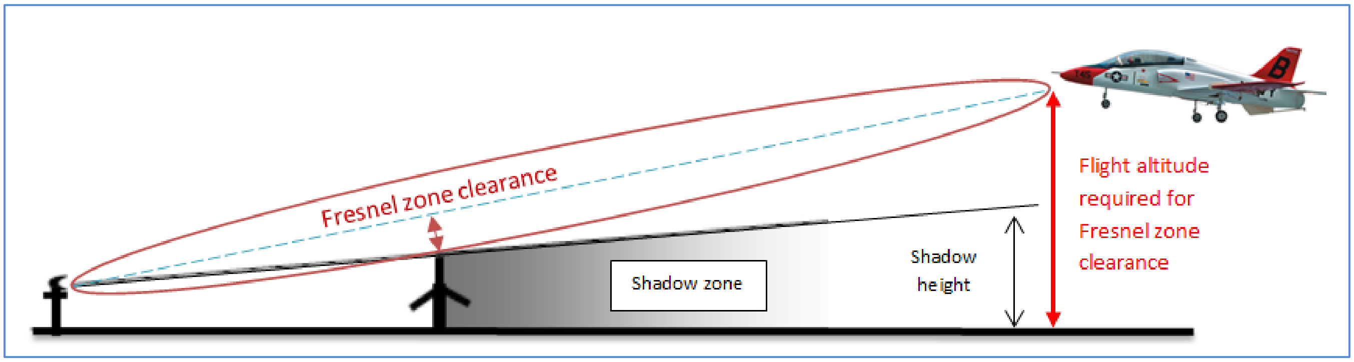

Figure 13: Fresnel zone clearance diagram

To calculate the flight altitude required for first Fresnel zone clearance, new variables are added to those present in the previous section. These new variables have to do with the calculation of the radius of Fresnel zones.

$$F_n = \sqrt{\frac{n\lambda D_{BT} D_{TP}}{D_{BT}+D_{TP}}} \qquad [6]$$

where:

F_n is the radius of the n^{th} Fresnel zone at a wind turbine that is distance D_{BT} from the TACAN beacon and distance D_{TP} from an aircraft
n is the number of the Fresnel zone in consideration
λ is the wavelength of the electromagnetic signal

We start with an equation similar to that of the previous section, adding the radius of the n^{th} Fresnel zone to the top of the wind turbine.

$$(kR + H_T + F_n)^2 = (kR + H_B)^2 + (D_{BT})^2 - 2(kR + H_B)(D_{BT}) \cos \alpha \qquad [7]$$

$$\left(kR + H_T + \sqrt{\frac{n\lambda D_{BT} D_{TP}}{D_{BT}+D_{TP}}}\right)^2 = (kR + H_B)^2 + (D_{BT})^2 - 2(kR + H_B)(D_{BT}) \cos \alpha \qquad [8]$$

We solve for *cos(α)*:

$$\cos\alpha = \frac{-\left(kR+H_T+\sqrt{\frac{n\lambda D_{BT}D_{TP}}{D_{BT}+D_{TP}}}\right)^2+(kR+H_B)^2+(D_{BT})^2}{2(kR+H_B)(D_{BT})} \quad [9]$$

We now consider the larger triangle that defines shadow height and also solve for *cos(α)*:

$$(kR+H_S)^2 = (kR+H_B)^2+(D_{BT}+D_{TP})^2-2(kR+H_B)(D_{BT}+D_{TP})\cos\alpha \quad [10]$$

$$\cos\alpha = \frac{-(kR+H_S)^2+(kR+H_B)^2+(D_{BT}+D_{TP})^2}{2(kR+H_B)(D_{BT}+D_{TP})} \quad [11]$$

We set the two equations for *cos(α)* equal to each other and solve for H_S:

$$\frac{-\left(kR+H_T+\sqrt{\frac{n\lambda D_{BT}D_{TP}}{D_{BT}+D_{TP}}}\right)^2+(kR+H_B)^2+(D_{BT})^2}{2(kR+H_B)(D_{BT})} = \frac{-(kR+H_S)^2+(kR+H_B)^2+(D_{BT}+D_{TP})^2}{2(kR+H_B)(D_{BT}+D_{TP})} \quad [12]$$

$$H_S = \sqrt{(kR+H_B)^2+(D_{TP})(D_{BT}+D_{TP})+\left(\frac{D_{BT}+D_{TP}}{D_{BT}}\right)\left(\left(kR+H_T+\sqrt{\frac{n\lambda D_{BT}D_{TP}}{D_{BT}+D_{TP}}}\right)^2-(kR+H_B)^2\right)}-kR \quad [13]$$

The equation above is used to populate a table that shows the minimum flight altitude for an aircraft for the first Fresnel zone of a direct ray to not be incident upon the wind turbine. The table below includes values calculated using the above equation and the information from the table in the previous section; thus it also contains turbine shadow heights, for comparative purposes between the various shadow heights and flight altitudes.

Table 4: Turbine shadowing vs. first Fresnel zone flight altitude

Distance beacon to aircraft (nmi)	Turbine shadow height (m)	Turbine shadow height (ft)	1st Fresnel zone flight height (m)	1st Fresnel zone flight altitude (ft)
10	128	420	135	443
20	271	890	382	1254
30	455	1492	644	2112
40	679	2226	945	3099
50	943	3093	1285	4217
60	1247	4092	1666	5466
70	1592	5224	2087	6847
80	1977	6487	2548	8360
90	2403	7883	3050	10005
100	2869	9412	3591	11783
110	3375	11072	4173	13692
120	3921	12865	4796	15734
130	4508	14790	5458	17908
140	5135	16847	6161	20214
150	5802	19037	6904	22652
160	6510	21358	7688	25222
170	7258	23812	8511	27924
180	8046	26397	9375	30758
190	8874	29115	10279	33724
200	9743	31964	11223	36822

The above table shows a clear increase in the flight altitude for first Fresnel zone clearance when compared to just the turbine shadow height. At a distance of 130 nautical miles away from the TACAN beacon, an aircraft would have to fly at an altitude of nearly 18,000 feet to safely clear the first Fresnel zone of a direct signal to the plane. This is an increase of 3,000+ feet over the altitude an aircraft would have to maintain to be safely above the shadow cast by a wind turbine. An analysis of the Instrument Approach Procedures at NAS Kingsville is performed next.

7. Instrument Approach Procedures Analysis

7.1 Instrument Approach Procedures Review

NAS Kingsville has the following IAPs (Instrument Approach Procedures):

- HI-ILS or LOC/DME RWY 13R
- ILS Z or LOC/DME RWY 13R
- HI-TACAN RWY 13R
- HI-TACAN RWY 35R
- TACAN RWY 13L/R
- TACAN RWY 17L
- TACAN RWY 31L/R
- TACAN RWY 35R
- TACAN Y RWY 17R
- TACAN Z RWY 17R

These IAPs must be adhered to when aircraft are performing instrument approaches to NAS Kingsville. IAPs that require aircraft to maneuver around or behind the Riviera Wind Farm (with regards to NAS Kingsville) require analysis for possible interference effects. With regards to approaches, any magnetic course bearing between 345 and 360 degrees on approach requires analysis. For missed approaches, any magnetic course bearing between 165 and 180 degrees requires analysis. The course bearings for the approach and missed approach mandated for each IAP and whether or not the IAPs require analysis for interference from Riviera Wind Farm are listed below. For reference, the airport diagram of NAS Kingsville is below the table for orientation with regards to magnetic course and runway orientation.

Table 5: Magnetic course bearing for approach and missed approach

IAP	Magnetic Course to Runway on Approach	Approach Analysis Required?	Magnetic Course from Runway on Missed Approach	Missed Approach Analysis Required?
HI-ILS or LOC/DME RWY 13R	130	No	180	Yes
ILS Z or LOC/DME RWY 13R	130	No	180	Yes
HI-TACAN RWY 13R	138	No	180	Yes
HI-TACAN RWY 35R	360	Yes	318	No
TACAN RWY 13L/R	138	No	180	Yes
TACAN RWY 17L	167	No	180	Yes
TACAN RWY 31L/R	291	Yes	318	No
TACAN RWY 35R	360	Yes	318	No
TACAN Y RWY 17R	146	No	N/A	N/A
TACAN Z RWY 17R	167	No	180	Yes

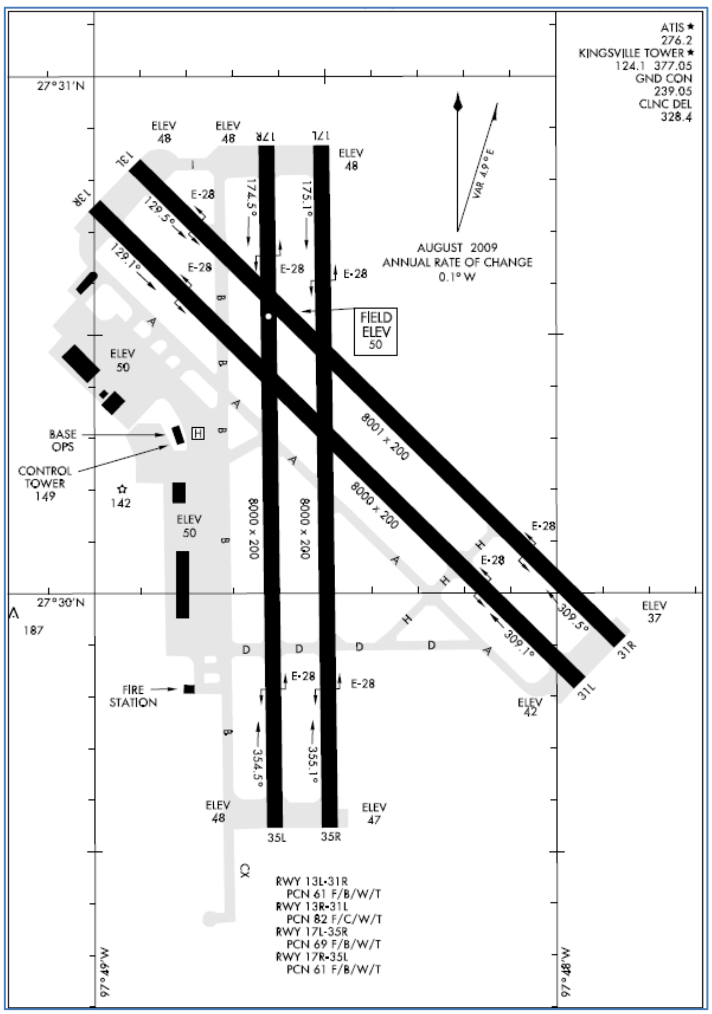

Figure 14: NAS Kingsville airport diagram

From the table it is apparent that IAPs HI-TACAN RWY 35R, TACAN RWY 31L/R, and TACAN RWY 35R require analysis for approach procedures. Furthermore, IAPs HI-ILS or LOC/DME RWY 13R, ILS Z or LOC/DME RWY 13R, HI-TACAN RWY 13R, TACAN RWY 13L/R, TACAN RWY 17L, and TACAN Z RWY 17R require analysis for their missed approach procedures. Since the missed approach procedures for each of these IAPs is the same, a single analysis for the procedure is performed.

7.2 Analysis of High-Altitude Instrument Approach Procedure HI-TACAN RWY 35

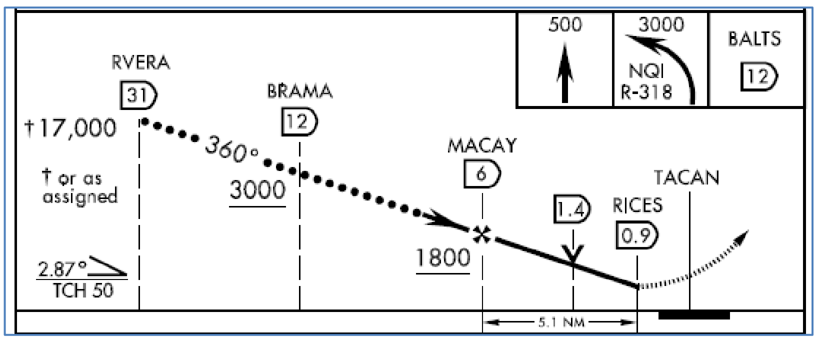

Figure 15: Altitude profile of IAP HI-TACAN RWY 35R

The altitude profile for this high-altitude IAP designates an altitude of 17,000 feet for an aircraft that is 31 nautical miles away from the NAS Kingsville TACAN, though a different altitude may be assigned. For second Fresnel zone clearance, a minimum height of approximately 2,500 feet AGL is required when the aircraft is 31 nmi from the beacon. Thus, there should not be a problem at this distance.

Once an aircraft reaches 12 nautical miles from the TACAN, it cannot be lower in altitude than 3,000 feet; this is a mandatory altitude, as evidenced by the fact that the value of 3,000 is underlined in the altitude figure above. At this distance, where the aircraft is above the western edge of the wind farm, the altitude required for first Fresnel zone clearance is 640 feet. Once the aircraft is within 10 nautical miles of the air station (past the Riviera Wind Farm), the potential for interference caused by the wind farm becomes negligible. For this approach pattern, the only first Fresnel zone clearance issue may occur when an aircraft has an assigned altitude of 3,000 feet AGL or less when the aircraft is more than 39 nautical miles from the TACAN beacon.

7.3 Analysis of Instrument Approach Procedure TACAN RWY 31L/R

Of the 10 IAPs mandated for NAS Kingsville, Instrument Approach Procedure TACAN RWY 31L/R is the most likely to experience interference due to the proposed Riviera Wind Farm. As seen in the figure below, this IAP is composed of a holding pattern that would partially be above the wind farm and an arcing transition to the magnetic approach bearing of 291 degrees. Both of these approach steps see the aircraft positioned above the proposed wind farm. A portion of the horizontal IAP is below with the corresponding vertical profile below it.

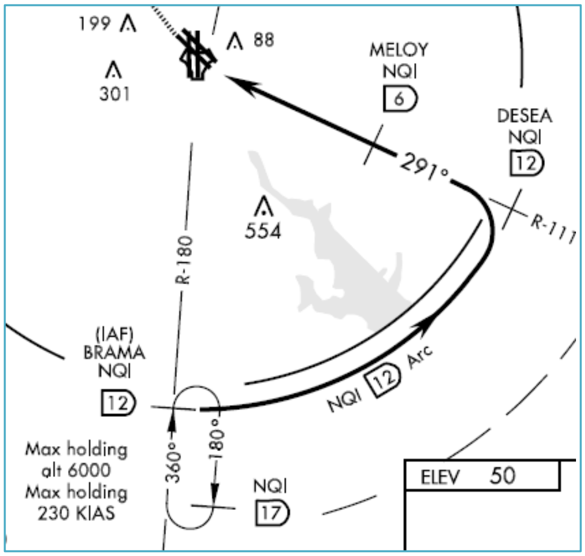

Figure 16: Detail of IAP TACAN RWY 31L/R

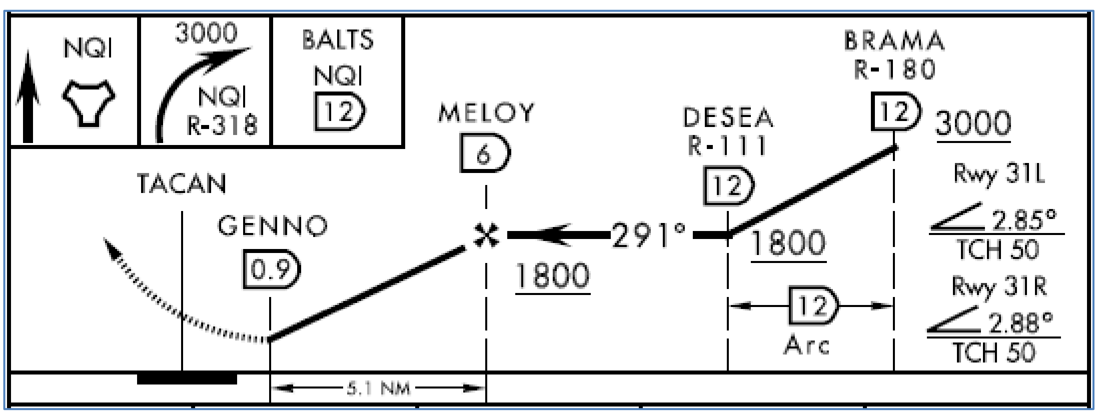

Figure 17: Vertical profile of IAP TACAN RWY 31L/R

As can be seen in the figures above, when an aircraft is in holding pattern BRAMA, it flies above and behind (with respect to the TACAN antenna) the western tip of the proposed wind farm. As was the case with the previous IAP, though, the minimum required height of the aircraft is 3000 feet AGL when it is in holding pattern BRAMA. Holding pattern BRAMA stretches to 17 nmi from the TACAN beacon. At 17 nmi, the second Fresnel zone clearance altitude is approximately 1,100 feet AGL, below the 3,000 foot altitude mandated for the holding pattern. Once the aircraft departs from the holding pattern and enters into the arc to reach position DESEA, it starts to lose altitude. Of interest is the lowest altitude the airplane is at while still over the proposed wind farm. Knowing that the wind farm is located between 165° and 180° and that the airplane is in the descending arc between 180° and 111°, we thus calculate:

$$length\ of\ arc = 2\pi * radius * \frac{arc\ angle}{360°} = 2\pi * 12\ nmi * \frac{69°}{360°} = 14.45\ nmi \quad [14]$$

$$descent\ rate = \frac{distance\ descended}{length\ of\ arc} = \frac{3000 - 1800\ ft}{14.45\ nmi} = 83\ ft/nmi \quad [15]$$

$$lowest\ altitude\ above\ wind\ farm = 3000\ ft - \frac{83\ ft}{nmi} * 14.45\ nmi * \frac{15°}{69°} = 2740\ ft \quad [16]$$

When an aircraft is above the eastern tip of the proposed wind farm, it is still at an altitude of approximately 2,700 ft. Given the 640 foot altitude for first Fresnel clearance at a 12 nmi distance, the aircraft is still 2,000 feet above the potential problem area.

7.4 Analysis of Instrument Approach Procedure TACAN RWY 35R

Instrument Approach Procedure TACAN RWY 35R is the final IAP of interest. This procedure involves an aircraft approaching NAS Kingsville at 360° bearing (thus radial R-180 w.r.t. the NAS), entering holding pattern BRAMA, and then continuing in straight descent to runway 35R. The vertical profile of this approach pattern is below.

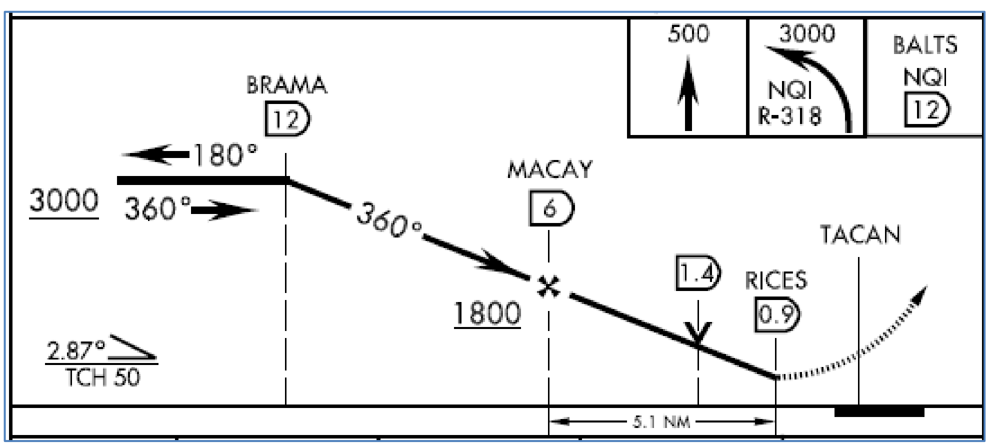

Figure 18: Vertical profile of IAP TACAN RWY 35R

This approach is very similar to the HI-TACAN RWY 35 approach, though the HI-TACAN approach is reserved for aircraft that approach from high altitudes. Since the same minimum altitudes apply for TACAN RWY 35R as HI-TACAN RWY 35, the analysis conducted for the HI-TACAN approach at 12 nautical miles and closer is valid for the non-high altitude approach to runway 35. There is no risk of the wind turbines being within the first Fresnel zone of the direct signal, creating the potential for signal loss.

7.5 Analysis of Missed Approach Procedure to Holding Pattern BRAMA

If an aircraft must enter missed approach procedures while following the HI-ILS or LOC/DME RWY 13R, ILS Z or LOC/DME RWY 13R, HI-TACAN RWY 13R, TACAN RWY 13L/R, TACAN RWY 17L, or TACAN Z RWY 17R instrument approach procedures, then the aircraft is required to make a climbing right turn to holding pattern BRAMA, whose northern-most tip is to be located above the proposed Riviera Wind Farm. Below is the missed approach diagram for IAP TACAN RWY 17L.

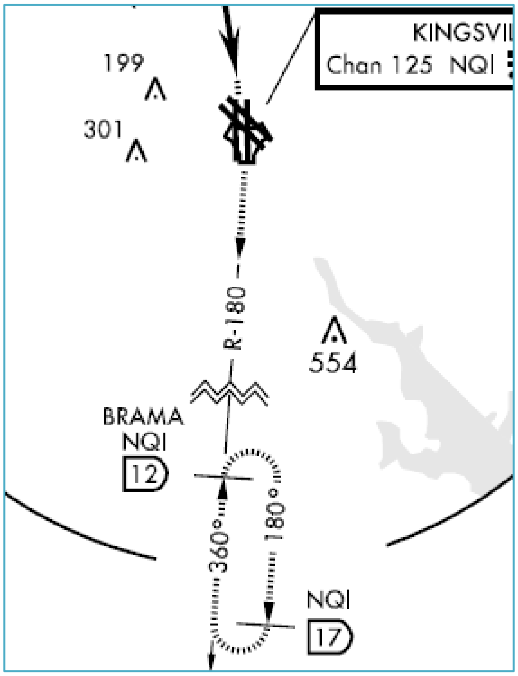

Figure 19: Detail of missed approach procedures

The required altitude for holding pattern BRAMA is 3,000 feet AGL. This is, as studied earlier, approximately 2,000 feet above the minimum flight altitude mandated by first Fresnel zone clearance and thus no Fresnel zone problems should occur.

7.6 Minimum Safe Altitude Analysis

All airports have a minimum safe altitude (MSA) designated within a certain distance of a navigational aid. For NAS Kingsville, there are three radial sectors around the airport, each with a different MSA. Our sector of interest (to the south of the airport) has a minimum safe altitude of 1,700 feet for aircraft within 25 nautical miles of the TACAN beacon, as seen in the figure below.

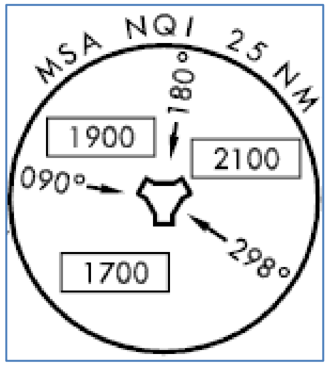

Figure 20: Minimum safe altitudes within 25 nmi of NAS Kingsville

The construction of the Riviera Wind Farm should not necessitate the elevation of the MSA in the sector between 90° and 298°.

7.7 Exclusion Zone Based on FAA Order 6820.10

Depending on the criteria that is deemed most critical in the maintenance of flight safety in the NAS Kingsville area, several turbine-free exclusion zones can be implemented to limit the proximity of wind turbines to the NAS Kingsville TACAN.

An important exclusion zone is laid forth in FAA Order 6820.10, which states that a structure containing metallic elements may not subtend an angle greater than 1.2° with respect to the TACAN beacon, measured from ground level at the beacon site. To determine the minimum distance between a TACAN beacon and a wind turbine for this criterion to be met, a spherical Earth should be assumed because ground elevations vary with location and azimuth. Also, Earth bulge (also known as Earth dip) should be taken into consideration:

$$distance\ between\ two\ points\ (meters) = 3570 * \sqrt{Earth\ dip\ (meters)} \qquad [17]$$

$$Earth\ dip\ (m) = \left(\frac{distance\ (m)}{3570}\right)^2 \quad [18]$$

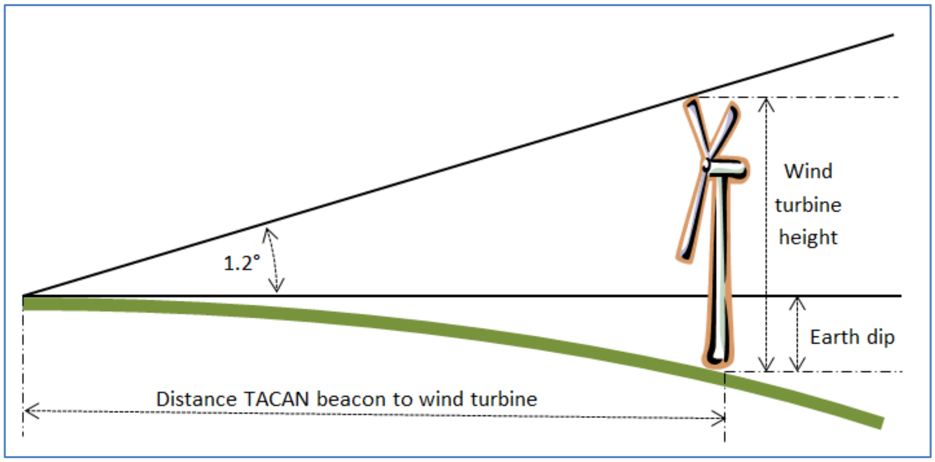

Figure 21: Effect of Earth dip on minimum distance between TACAN beacon and wind turbine

The height of the proposed Vestas wind turbines is 125 meters. A modified version of the equation from section 4.4 is adopted, taking into account the equation for Earth dip:

$$\tan(angle\ subtended\ by\ wind\ turbine) = \frac{height\ wind\ turbine - Earth\ dip\ at\ distance}{distance\ between\ beacon\ and\ turbine} \quad [19]$$

$$\tan(1.2°) = \frac{125 - \left(\frac{d_{min}}{3570}\right)^2}{d_{min}} \quad [20]$$

$$d_{min} = 5840\ m = 3.15\ nautical\ miles \quad [21]$$

Thus, according to FAA Order 6820.10, which sets the navigational aid siting rules, a 125 meter tall wind turbine may not be located within 3.15 nmi of the TACAN beacon. The following figure portrays this exclusion zone.

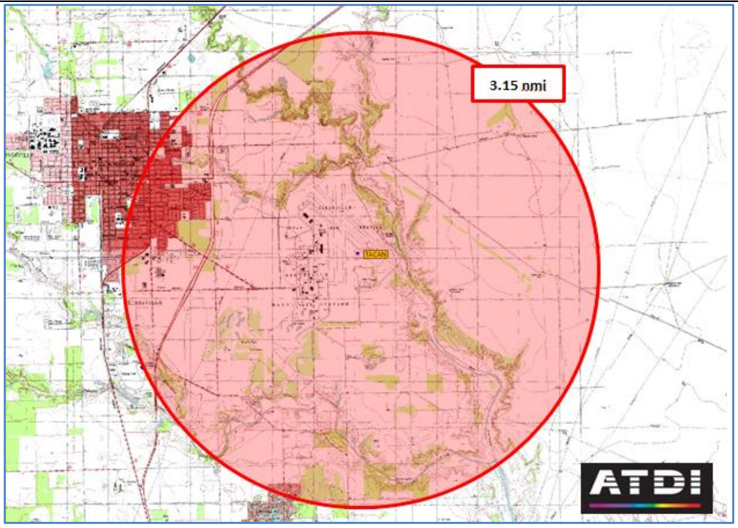

Figure 22: Exclusion zone based on FAA Order 6820.10

To verify the validity of the 3.15 nmi calculated minimum distance and to account for variations in the nearby terrain, the clearance contour function was run in ATDI software. The below figure portrays the calculated 3.15 nmi exclusion zone with one that takes into account local terrain. The exclusion zone provided by the software ranges from 2.9 nmi to 3.3 nmi from the TACAN beacon, dependent on azimuth. The 3.15 nmi calculated value is in dark red while the contour created by the software is bright red.

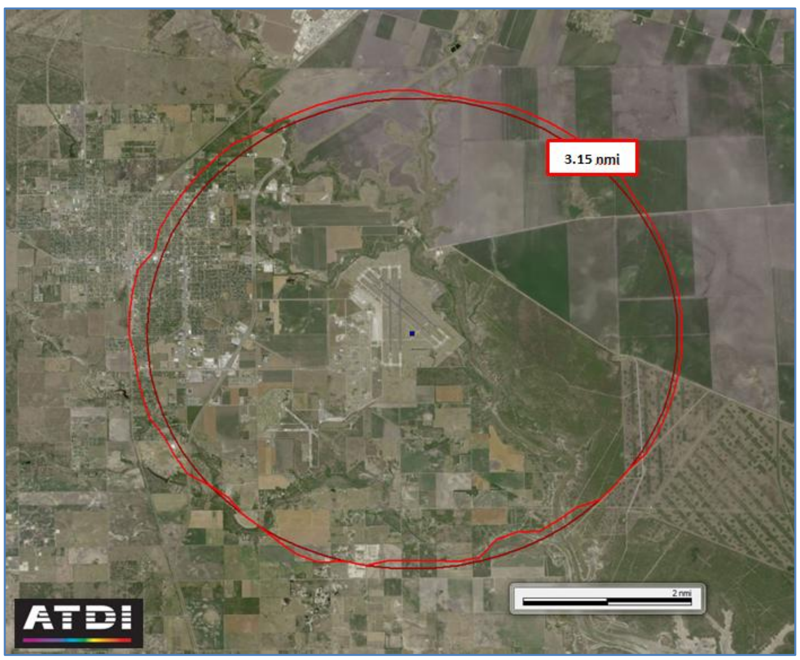

Figure 23: 1.2° rule per calculation and software simulation

It is apparent, from both the calculation and the output of the software simulation, that the proposed Riviera Wind Farm does not violate the 1.2 degree rule set forth in FAA Order 6820.10. Yet, the 3.15 nautical mile boundary should not be forgotten and may be brought into effect if other proposed wind farms are to be developed closer to NAS Kingsville.

7.8 Exclusion Zones Based on Minimum Safe Altitudes

Further possible exclusion zones are calculated based upon interference-free communication at all minimum safe altitudes within 25 nautical miles of NAS Kingsville. The table below displays the minimum distances between wind turbines and a TACAN beacon for various criteria explored earlier in this report, based upon first Fresnel zone clearance requirements stated by FAA Order 6820.10. The minimum safe altitude calculations assume a worst case scenario; an aircraft is located 25 nautical miles away from the TACAN beacon at the given minimum flight altitude. The equation used to solve for the minimum distances is based on Equation 12, found in section 6.2, though total distance between beacon and aircraft D_T is considered instead of the distance between turbine and aircraft D_{TP}; thus $D_T = D_{BT}+D_{TP}$ and $D_{TP}=D_T-D_{BT}$.

$$\frac{-\left(kR+H_T+\sqrt{\frac{n\lambda D_{BT}(D_T-D_{BT})}{D_T}}\right)^2+(kR+H_B)^2+(D_{BT})^2}{D_{BT}}=\frac{-(kR+H_S)^2+(kR+H_B)^2+(D_T)^2}{D_T} \quad [22]$$

$$\frac{-\left(kR+H_T+\sqrt{\frac{n\lambda D_{BT}(D_T-D_{BT})}{D_T}}\right)^2+(kR+H_B)^2+(D_{BT})^2}{D_{BT}}+\frac{(kR+H_S)^2-(kR+H_B)^2-(D_T)^2}{D_T}=0 \quad [23]$$

With the equation set to zero and all but one of the variables known, the distance between beacon and turbine D_{BT} is solved for and the calculated values are in the table below.

Table 6: Minimum distances between TACAN and wind turbines according to MSAs

Criteria	Minimum distance TACAN to WT
2,100 ft AGL minimum flight altitude at 25 nmi from beacon (MSA)	7.6 nmi
1,900 ft AGL minimum flight altitude at 25 nmi from beacon (MSA)	8.5 nmi
1,700 ft AGL minimum flight altitude at 25 nmi from beacon (MSA)	9.8 nmi

As explored in an earlier section, there are three regions centered around the NAS Kingsville TACAN with differing minimum safe altitudes. The general radii of the exclusion zones for the given minimum safe altitudes (regardless of the azimuths at which they are in effect) are presented in the next figure with the previously calculated 3.15 nmi radius calculated for Order 6820.10. The location of the proposed Riviera Wind Farm is shown as well for reference. The wind farm is located just outside the bounds of the exclusion zone required for the 1700 foot minimum safe altitude, the one in effect for the azimuths at which the farm is to be located.

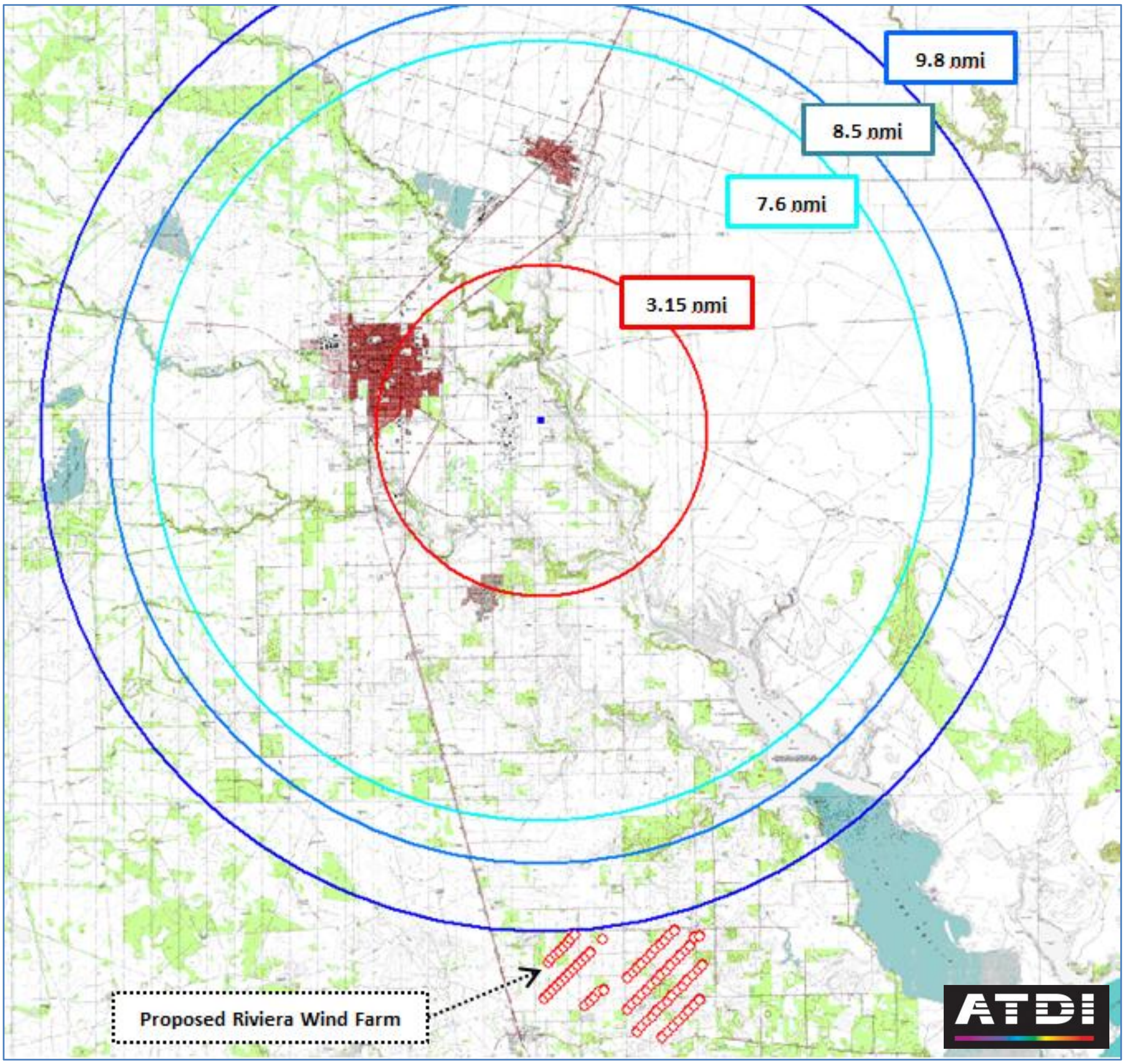

Figure 24: Proposed wind turbine exclusion zones based upon clearance criteria

Again, the calculated values are based on flat earth. To bring in terrain variations, ATDI software was employed. The figure below shows the calculated contours and those provided as a result of software simulations for the three minimum safe altitudes. In each case, the darker radius is the calculated value while the lighter one is the one produced by the software simulation.

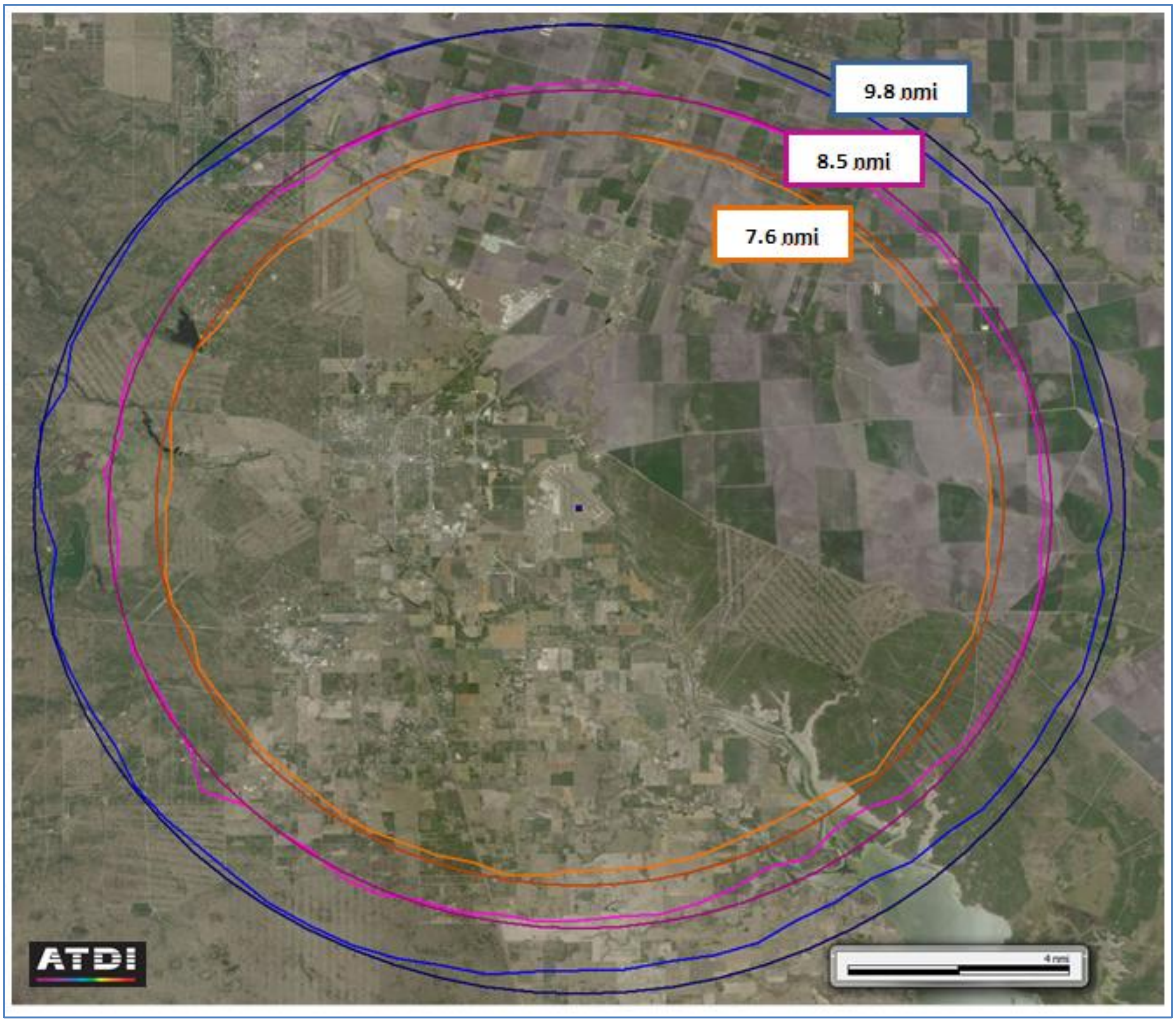

Figure 25: MSA-based exclusion zones

In the two figures above, the proposed Riviera Wind Farm does not fall within the bounds of any of the radii calculated. Yet, a combination of the exclusion zones based on the azimuths at which they are in effect, as seen in the next two figures, may be employed in studying future wind farm proposals. The first figure is based on the calculated exclusion zones while the figure that follows it is a product of the ATDI software simulation.

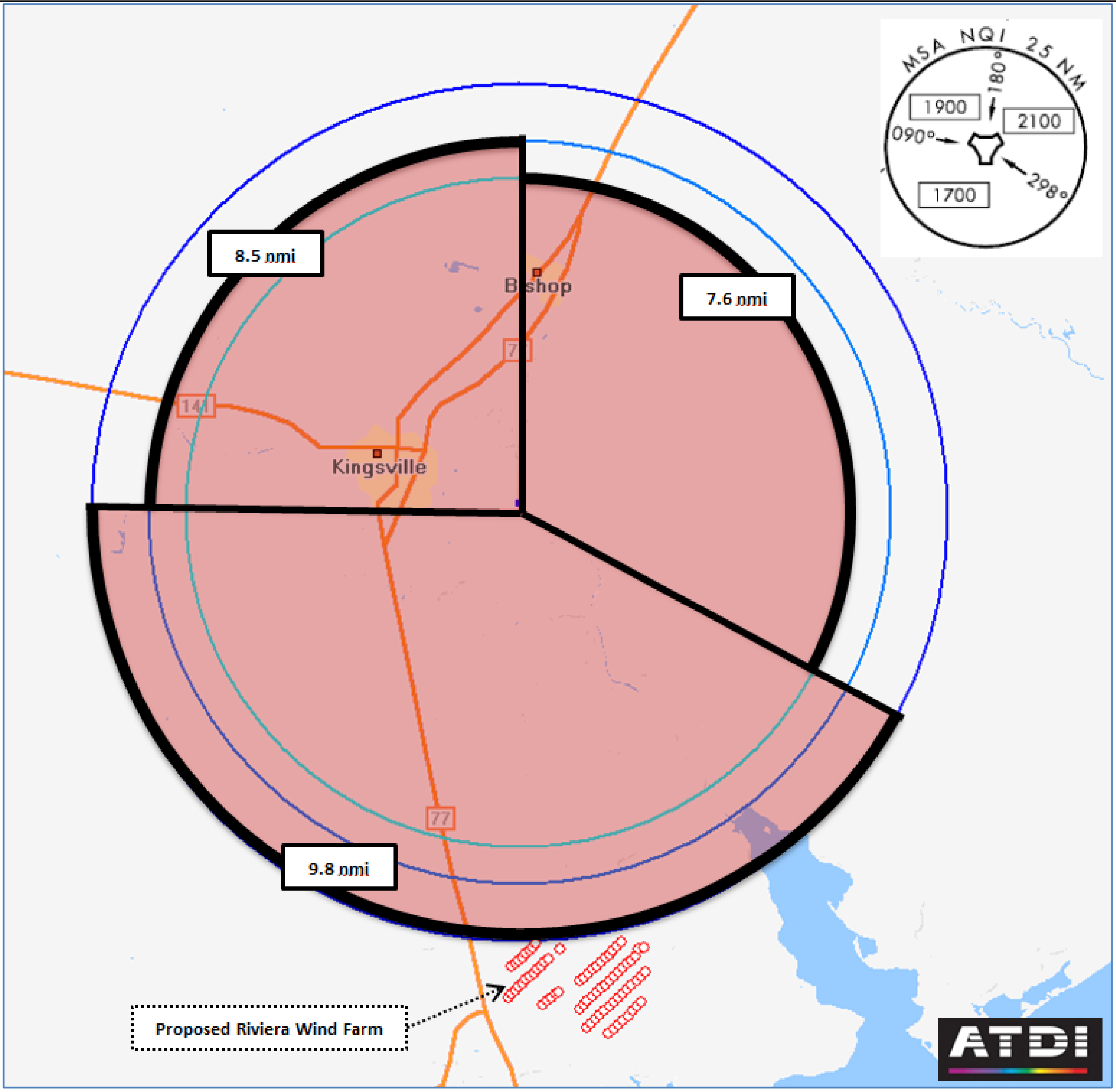

Figure 26: Exclusion zone compilation based upon minimum safe altitudes

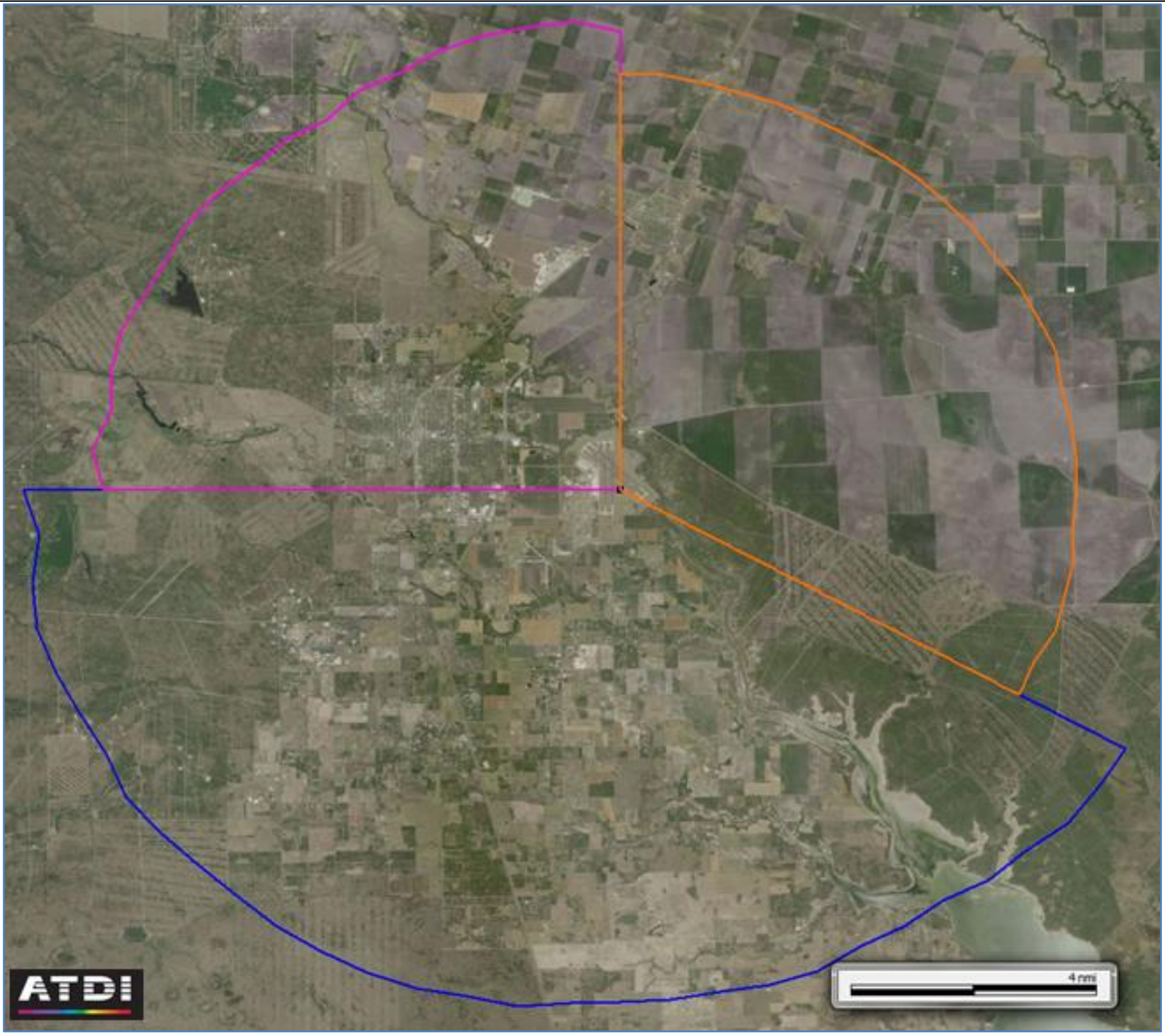

Figure 27: Sectorized exclusion zones computed by software simulation

7.9 Exclusion Zones Based on Lower Bounds of Standard Service Volumes

Wind turbine exclusion zones may also be calculated and simulated for the lower bounds of the standard service volumes discussed earlier in this report. As detailed in section 4.4 of this report, the lower bounds of these service volumes allow for safe communication with aircraft that are at 1,000 ft AGL at distances of 25 nmi (for the Terminal SSV) and 40 nmi (for the Low and High Altitude SSVs) from a navigational aid antenna. However, these are tough criteria to meet and Notices to Airmen

(NOTAM) may be issued to warn of weaker navaid communication at such low altitudes. If based upon the 1,000 ft AGL minimum flight altitude at 25 nmi from the TACAN beacon, the exclusion zone would be 16.8 nmi. This can be deemed unreasonable and is only presented as a point of interest, as it is common for there to be obstructions at the lower bounds of standard service volumes. If a minimum distance between TACAN and wind turbine is calculated such that the lower bound of the Low and High Altitude SSVs is unaffected, the result places the turbines out of line-of-sight. The calculated value and result of ATDI software simulation for an aircraft at 1,000 feet AGL at 25 nmi is presented in the figure below (simulation result in green and calculated radius in brown).

Table 7: Exclusion zones for standard service volumes

Criteria	Minimum distance TACAN to WT
1,000 ft AGL minimum flight altitude at 25 nmi from beacon (SSV)	16.8 nmi
1,000 ft AGL minimum flight altitude at 40 nmi from beacon (SSV)	Beyond LOS

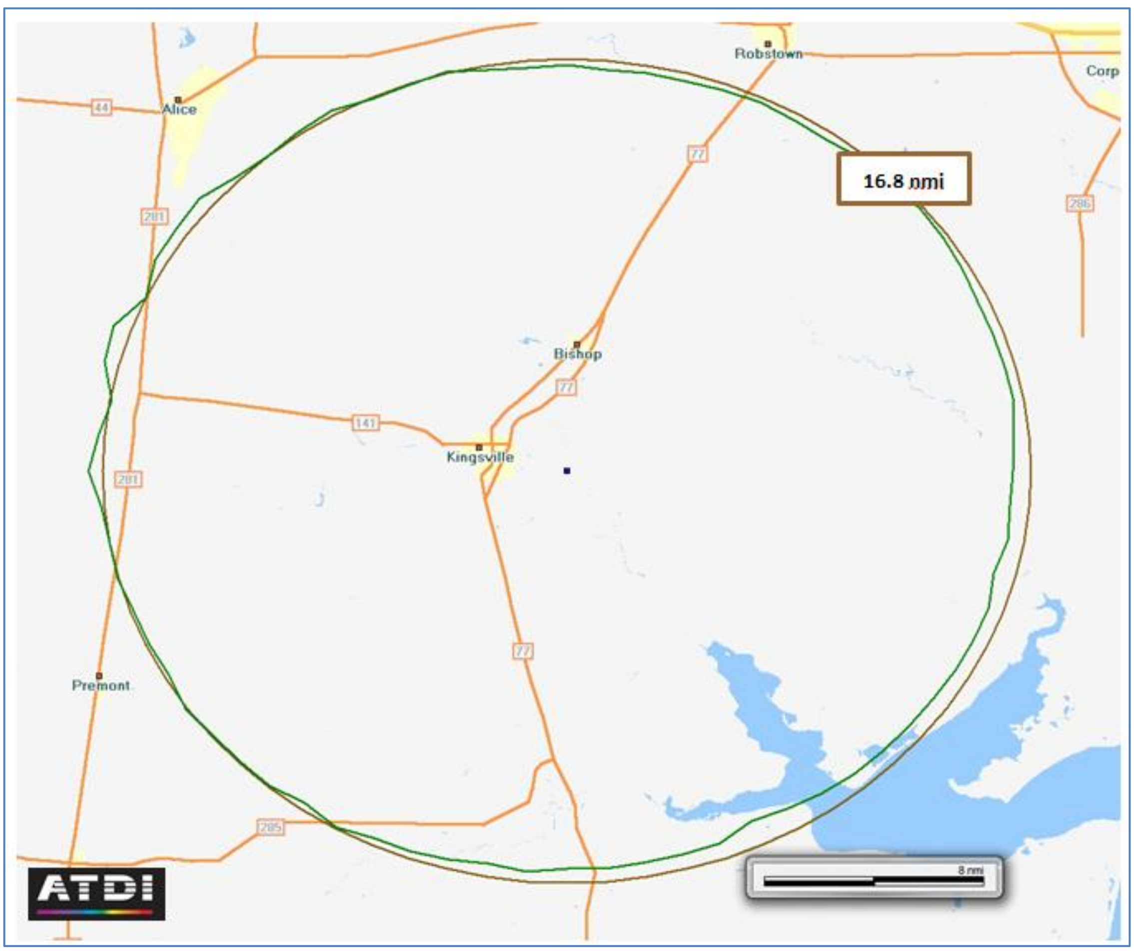

Figure 28: Standard service volume

8. Electromagnetic Interference Studies

8.1 Electromagnetic Interference Effects of Wind Turbines

An early study on the adverse effects that wind turbines have upon communications, navigational, and surveillance systems was conducted at the University of Michigan by Dipak L. Sengupta in the early 1980s [12]. In the report, Sengupta presents several equations for the quantifying of the interference introduced by wind turbines to FM broadcast, TV reception, and VORs, among other wireless systems. Unfortunately, as is even evident in this early study, the amount of scattered or secondary energy that arrives at an airborne receiver is highly dependent on wind speed and direction, and thus varies greatly; "the rotating blades act as a time varying multipath source." The following is an excerpt from the study findings that is pertinent to TACAN, though the VOR system is studied specifically:

> The VOR and DVOR (Doppler VOR) systems are extensively used for (commercial) aircraft navigation over the continental United States, and in fact over the world. Due to this and their apparent vulnerability, we chose to analyze the impact of a rotating WT on the performance of those two systems. The analysis was carried out by comparing the direct and WT-scattered VOR (DVOR) signals at an aircraft and then using the detection characteristics of the receivers to estimate the resulting error in the predicted aircraft locations. The analytical procedures employed are logical extensions of those the FAA (Federal Aviation Administration) found acceptable in the case of static scatterers, and showed that the interference when the WT blades are rotating is less troublesome then when the blades are stationary. It therefore follows that the siting of a WT can be carried out according to the standard guidelines established by the FAA.

The results of the study provide for a very interesting point: that the interference from a rotating wind turbine is less troublesome than that of a stationary turbine. This result is contrary to what is seen for primary surveillance radar (PSR), where the rotating blades are able to defeat the Doppler processing techniques of the system, allowing for the appearance of the turbines on the screen of radar operators. A symptom that is common to both types of systems, though, is the creation of a region of weakened signal behind the wind turbine (due to reflection and refraction) when a wind turbine is within LOS, a point not covered by the Sengupta report. The Sengupta report, though, does validate the critical innermost exclusion zone defined by FAA Order 6820.10 and evaluated in the previous section.

8.2 Wind Farms and their Effect on Radio Navigation Aids

A paper presented in Toulouse, France, in 2006 by Simbo Odunaiya of Ohio University [13] offers a parallel to the current situation at NAS Kingsville. Entitled 'Wind Farms and Their Effect on Radio Navigation Aids,' the site under investigation featured a proposed wind farm to be erected approximately 6.8 to 10.5 nautical miles away from a VOR serving a regional airport, in the second quadrant. The report states that there were 40 wind turbines to be erected, of proportions roughly equivalent to those that are to be part of the Riviera Wind Farm. Using proprietary Ohio University software, two circular flight paths are modeled, centered around the VOR of interest; one orbital flight occurs at 1,000 feet AGL at a distance of 40 nmi (0.24 degree angle w.r.t. the horizon) to the VOR while the second occurs at 5,000 feet AGL at a distance of 40 nmi (1.2 degree angle w.r.t. the horizon) to the VOR. The predicted error in bearing for the two trials is located in the table below.

Table 8: Results of orbital flight simulations of Ohio University study

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

The greater error at the lower altitude can be attributed to multipath, shadowing, and possible second Fresnel zone infringement by the wind turbines. While for the three quadrants where the turbines are not to be located see a three-fold increase in error with a drop in altitude from 5,000 ft AGL to 1,000 ft AGL, the quadrant containing wind turbines sees a five-fold increase in error. This validates the fact that when an aircraft is at a lower altitude, it is more likely to experience distance and bearing errors due to multipath scattering and reflections within the second Fresnel zone. For TACAN beacons located at airports, these lower altitudes must be protected to allow for the safe operation of the airport.

9. Conclusion

When located near enough to a ground-based TACAN beacon, wind turbines may cause harmful interference. The interference possible is mainly due to shadowing and second Fresnel zone clearance. Signal scattering outside of the second Fresnel zone is likely not to cause major interference due to the Transponder Dead Time and Echo Suppression Dead Time processing methods, and the restrictions placed upon received pulse pair characteristics found in TACAN transponders.

As with other air traffic control systems (i.e. primary surveillance radar and monopulse secondary surveillance radar), large structures in the immediate vicinity of the system can potentially create shadow regions of diminished electromagnetic signal. Such regions may even be completely devoid of the signal. The shadow regions created dictate minimum altitudes for aircraft to maintain in order to be above the shadow heights, thus minimizing the risk of no or diminished signal strength.

An important aspect to consider in TACAN analysis is Fresnel zone clearance. Because the vertically polarized TACAN signals are susceptible to destructive interference and the creation of nulls, it is essential to maintain a certain clearance between an obstruction and the direct ray of the TACAN signal. All energy within the first Fresnel zone of a signal sums positively to intensify the overall energy of the signal at the receiver. Energy within the second Fresnel zone, though, subtracts from the overall energy. If energy within the second Fresnel zone of a direct signal impacts upon an obstruction and destructive summation occurs at a receiver, an aircraft may be left without a valid signal and thus without vital direction and distance information. Thus, it is stated in the FAA Order 6820.10 that the first Fresnel zone should be clear of obstructing objects so that full power is received by a TACAN receiver and the occurrence of nulls and fading is minimized. First Fresnel zone clearance adds to the shadow height of shadow regions, establishing safe flight heights at greater altitudes than when shadow regions are considered by themselves. Wind turbine exclusion zones may be established based on FAA Order 6820.10 and the safety requirements and necessary minimum safe flight altitudes mandated by an airport. Thus, there are several options for turbine exclusion zones.

The absolute minimum distance between a wind turbine and a TACAN beacon is defined by FAA Order 6820.10, which prohibits a metallic structure from subtending an angle greater than 1.2 degrees with respect to the TACAN beacon; thus the specified model wind turbine should not be within 3.15 nautical miles of the TACAN beacon.

The choice of turbine exclusion zones continues with requirements set forth by standard service volumes for navigational aids and minimum safe altitudes within 25 nautical miles of NAS Kingsville. For the minimum safe altitudes mandated around NAS Kingsville for aircraft 25 nmi from the TACAN beacon at 2,100 ft AGL, 1,900 ft AGL, and 1,700 ft AGL, wind turbines should be no closer than 7.6 nmi, 8.5 nmi, and 9.8 nmi, respectively. For the lower bound of the terminal standard service volume (aircraft at 1,000 ft AGL, 25 nmi from beacon) to be unaffected, wind turbines should not be closer than 16.8 nmi.

Based upon the minimum safe altitudes set forth for aircraft operating within 25 nautical miles of the TACAN antenna, an exclusion zone featuring a combination of the 7.6 nmi, 8.5 nmi, and 9.8 nmi exclusion zones is viable. Each of the three sectors around NAS Kingsville would thus have a different minimum distance.

Ultimately, Riviera wind farm should not significantly impact TACAN operation at NAS Kingsville, though the determined exclusion zones should be considered for future wind farm projects that may see wind turbines being brought closer to the TACAN beacon. The selection of the exclusion zone radius is dependent on the day-to-day operations and safety requirements necessary at the airport in question. While the radius defined by FAA Order 6820.10 is a minimum, the radii based on minimum safe altitudes are also important and should be considered.

10. References

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11. Appendix—Summary of Cumulative Effects

Though the potential interference effects of a limited number of wind turbines may be deemed negligible or even acceptable to an existing TACAN beacon, consideration should be provided for the possible interference effects of a large number of turbines.

The TACAN beacon mainly experiences interference due to two effects, shadowing and null creation, both of which are based upon signal waves being incident upon an obstruction. Ultimately, the number of turbines within line-of-sight determines the amount of reflective surfaces that may interfere in communication between an airborne transponder and a ground-based TACAN beacon and vice versa.

In terms of shadowing, the greater the number of wind turbines present in the vicinity of a TACAN beacon, the greater the shadow volume that is cast. Unless shadow volumes cast by wind turbines intersect, the total shadow volume cast by a group of turbines is directly related to the number of wind turbines within line-of-sight of the TACAN beacon.

In terms of null creation, the greater the number of wind turbines present, the larger the amount of surfaces upon which signals can be incident, reflected, and negatively summed at the aircraft transponder. Also possible are multiple reflections between several wind turbines, leading to an increase in the probability of reflections overall.

If wind turbines are located beyond the bounds necessary to satisfy the FAA 1.2° rule and beyond the calculated MSA protection zones, the amount of energy reflected by the wind turbines, no matter their number, may be considered negligible with little to no interference expected.