IMPACT OF RIVIERA WIND FARM ON MONOPULSE SECONDARY SURVEILLANCE RADAR AT KINGSVILLE NAVAL AIR STATION

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Executive Summary

Wind turbines can affect the propagation of electromagnetic energy from an MSSR to an aircraft, or vice versa. The potential impact of the wind turbines to an electromagnetic emission depends on a number of factors such as the wind turbine radar-cross-section (RCS), the terrain, and the position and altitude of the radar including its technical parameters. An in-depth analysis was undertaken to understand the impact of wind turbines on electromagnetic emissions. The analysis was based on the guidelines provided in "Guidelines on How to Assess the Potential Impact of Wind Turbines on Surveillance Sensors" by the European Organisation for the Safety of Air Navigation.

To assess the propagation of the MSSR signal over the Riviera Wind Farm four different scenarios are studied:

- Line-of-Sight
- Shadow zone
- False target report
- Position accuracy

The analyses of the four scenarios lead to the conclusion that **minimum flight altitude of 492 feet** (above-ground-level) is required in the Riviera wind farm vicinity to avoid potential adverse effects.

The table below summarizes the result of the four scenarios:

	1. Line-of-Sight	**2. Shadow Zone**	**3. False Target**	**4. Position Accuracy**
Impact	Obstruction could lead to shadow, false target, and position error effects	Degradation in Probability of Detection	Multiple replies to MSSR generating false targets	Target bearing detection error
Assessment Result	Riviera wind farm is within LOS of the MSSR	Shadow height = 492 ft	Interrogation-signal reflection distance = 5,118 ft	Reply-signal reflection strength is minimal
Issue	**Potential issue**: Requires shadow zone, false target, and position accuracy analyses	**Potential issue**: minimum 492 feet AGL flight altitude is required	**No potential issue:** MSSR Interrogator-Side-Lobe-Suppression technique protects up to 17,224 ft	**No potential issue**: Direct reply-signal is significantly greater to overcome potential interference

The MSSR is less subject to experience interference problems when compared with a PSR system. Unlike primary radar, which passively listens for the echo from the target, SSR is a cooperative active system that requires a response from the target. The MSSR ground station sends out a radar pulse, which "interrogates" the target. The target replies to this interrogation via a transponder, with information about the target. The interrogation and reply occur at different frequencies, 1030 MHz for the interrogation and 1090 MHz for the reply. The advantage of using a transponder on the target is threefold:

1. Since the ground station does not receive an echo from the target, the effective range of the MSSR system can be extended and lower power transmitters used;
2. The interrogation and reply are transmitted on two different frequencies, which means that detection of unwanted echoes can be avoided;
3. The use of a transponder on the target allows information to be exchanged (in coded messages), in addition to providing information about the location of the target.

Since MSSR communication is transponder-based and the MSSR system employs echo suppression technology, reflected RF energy does not significantly interfere with the system's normal operation. Yet, care should still be practiced in the siting of large obstructions, including wind turbines, between the MSSR antenna and volumes of airspace that aircraft normally occupy.

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1. Abbreviations

AMSL	Above Mean Sea Level
ATC	Air Traffic Control
CAA	Civil Aviation Authority
CRC	Cyclic Redundancy Check
DASR	Digital Airport Surveillance Radar
FRUIT	False Replies Unsynchronized In Time
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
LOS	Line of Sight
m	meter
MCEB	Military Communications-Electronics Board
MW	Mega Watt
MSSR	Monopulse Secondary Surveillance Radar
NASA	National Aeronautics and Space Administration
NASK	Naval Air Station – Kingsville
NLOS	Non-Line-of-Sight
nmi	Nautical Mile
NED	National Elevation Dataset
NTIA	National Telecommunications and Information Administration
PCR	Pulse Compression Ratio
PSR	Primary Surveillance Radar
RCS	Radar Cross Section
RF	Radio Frequency
SDTS	Spatial Data Transfer Standard
SFAF	Standard Frequency Action Format
SRTM	Shuttle Radar Topography Mission
STC	Sensitivity Time Control
Tx/Rx	Transmitter/ Receiver
USGS	United States Geological Survey
WT	Wind Turbine

2. Introduction

2.1 Overview of Monopulse Secondary Surveillance Radar (MSSR)

MSSR provides additional information about the target and is used in conjunction with the PSR system. The MSSR station sends out an interrogation signal to the target. The target responds back to the interrogation via a transponder with information about itself. By use of the MSSR system, the detection/communication range extends out to 120 nmi with a lower power transmitter. Comparably, a typical PSR range is 60 nmi with transmit power that is 23 dB higher than the MSSR. The interrogation signal of the MSSR is transmitted at 1030 MHz and the response signal is received at 1090 MHz in order to minimize detection of unwanted echoes. In addition to providing the location information of the target, the aircraft transponder can exchange information with the MSSR in coded messages.

2.2 Objective

As an extension to the previous report on Raytheon DASR-11 Primary Surveillance Radar at Naval Air Station Kingsville (NASK), the objective of this report is to analyze potential interference effects of the projected Riviera wind farm on DASR-11 Monopulse Secondary Surveillance Radar (MSSR) located at NASK. ATDI's RF planning software, HTZ Warfare, was utilized to efficiently consider high-resolution cartographic data and to automate theoretical calculations by applying formulas on the projected wind turbines in Riviera Wind Farm for its cumulative effect consideration. The four scenarios below are considered to determine the potential effect of Riviera Wind Farm.

The four areas of focus that may lead to adverse effects are:

- Radar Line-of-Sight calculation
- 3D Shadow zone calculation
- False target detection
- Position accuracy

MSSR is a cooperative active system that requires a reply from a target which is used in conjunction with the PSR system to provide additional information about the target. The MSSR ground station relies on the transmission of a radar signal unlike PSR, which listens for the 'echo' from the target. Targets of an MSSR ground station are required to carry a transponder to reply to radar interrogation.

Radar Line-of-Sight Calculation and 3D Shadow Zone Calculation:
Wind turbines obstructing the direct path between radar and target of interest creating a shadow zone within which communication between targets may be lost or degraded due to the obstruction. Firstly, a mathematical approach is employed to determine whether the Riviera wind farm is within MSSR LOS range and can thus potentially create a shadow zone. Given the curvature of the earth, a minimum distance is also calculated for which the wind farm would be completely out of range of the radar. The LOS analysis is also simulated using ATDI HTZ Warfare to utilize high-resolution cartographic information. Once it is determined that a shadow zone is created, calculation of the shadow is performed for three-dimensions to further consider its volume.

False target reports:
If the path difference is smaller than the length of the transmission then the direct and indirect (reflected) signals will overlap causing code corruption. However, if the target is at a higher altitude that the path difference is large, a false target may be plotted at a similar bearing to the actual target but at a longer distance. MSSR systems do record maps of static clutters to normalize reflected responses; however, since wind turbines are not static objects – velocity and yaw angle of the blades change according to variable wind – this technique is not as efficient on such moving objects. This will only occur if the reflection signal from the target is large enough to trigger the MSSR receiver. On the other hand, MSSR receiver sensitivity is altered/calibrated using Sensitivity Time Control (STC) technique to adjust the video display (i.e. it indirectly adjusts the gain – receiver sensitivity). Hence, using this technique does not plot detected signals if they are below a reference signal.

Position Accuracy:
When there is a successful interrogation via reflecting a wind turbine, the reply to reach the MSSR can be via either reflected path or direct path. It is also possible that the reflected reply is below the receiver threshold, which then is ignored, and the direct reply successfully reaches the MSSR receiver. However, if the reflected reply is detected in the main beam, rather than the sidelobes for suppression, then the problem of the target being plotted at wrong bearing may occur.

- An ***MSSR Mode-S system*** calculates the bearing of an aircraft using the orientation of the EM wave as it reaches the antenna. Reflections of the transponder signal from nearby objects (such as wind turbines) will combine with the direct signal in such a way that the wave-front is distorted. This can lead to errors in the bearing calculation. [17]

- In a ***sliding window system***, the reflected energy arriving back at the antenna will be dispersed in azimuth, such that it is no longer centered on the true target azimuth. This will 'fool' the algorithms used by many SSRs to determine azimuth, and an error will occur. Under these conditions (small path difference) range measurement error may also occur due to the

combination of the direct and reflected signals and the measurement of the time of arrival of the SSR reply may be altered. This effect may occur to targets located further away than the wind turbine and in the same azimuth region. [17]

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 cartographic 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 refer 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 be a digitized paper map, satellite photo or aerial photo. For this study, ATDI created both a 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 neat line 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:

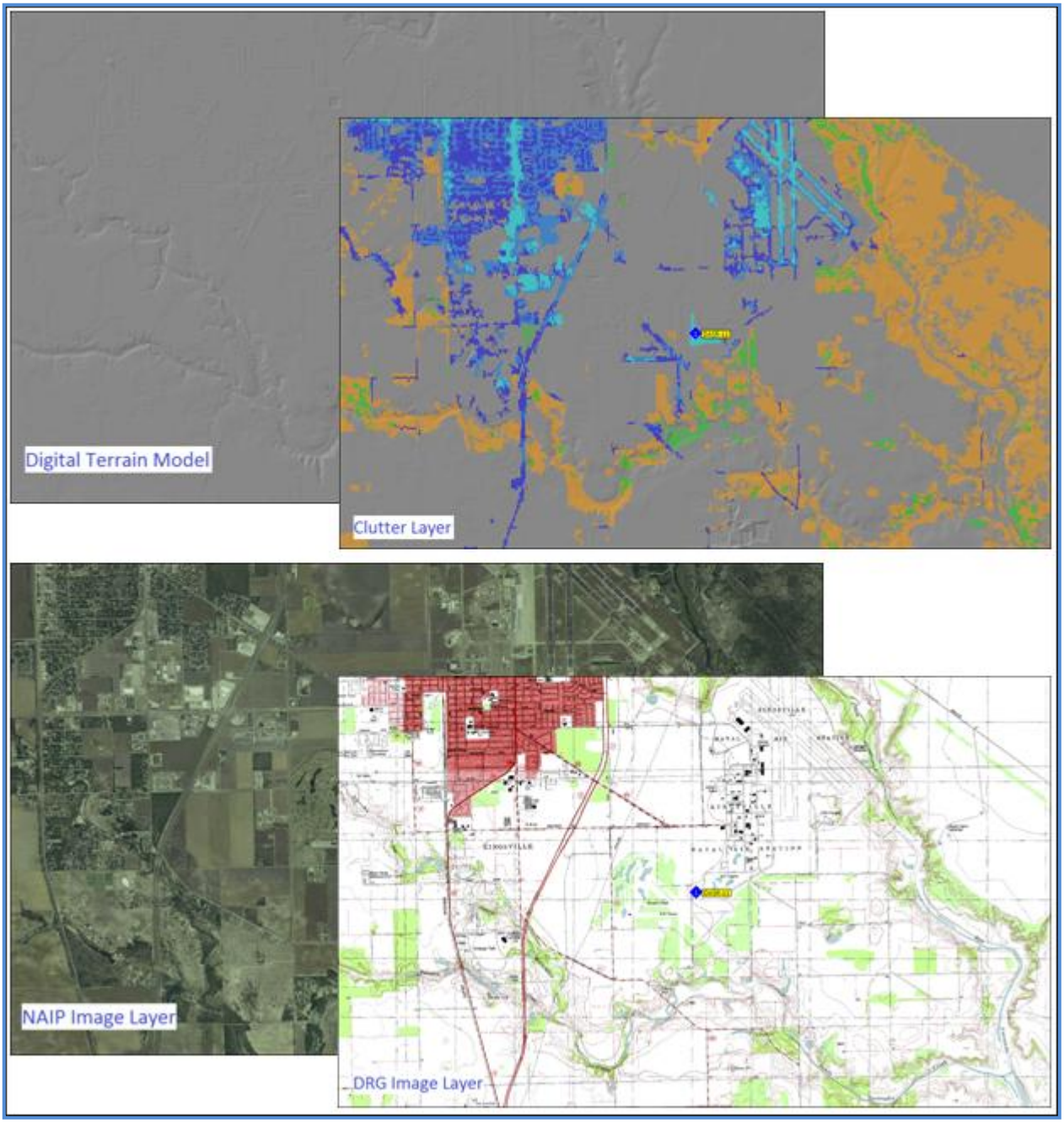

Figure 1: Cartography in HTZ Warfare

4. Wind Turbine Radar-LOS Calculation

4.1 LOS Analysis Basics

A wind turbine may be deemed as out of the LOS of the radar when it is located at a great enough distance or when the LOS is obstructed so that radio waves do not influence upon its physical structure. Due to the curvature of the earth, when a turbine is located at a great enough distance it will be hidden by the horizon, given smooth terrain. When a geological formation (usually of a greater elevation) is in the direct LOS between radar and a wind turbine, again the turbine is hidden from the radar at a much shorter distance due to the curvature of the earth.

As can be seen in the image below, the terrain in Kleberg County, especially in the area where the Riviera Wind Farm is proposed, is mostly flat with little elevation change. The image below was captured during the site visit (June 3, 2010) to NAS Kingsville and the surrounding area.

Figure 2: Image captured during Kingsville region site survey

Somewhat greater care must be taken in LOS analysis due to the phenomenon of diffraction. Diffraction allows for the bending of radio waves around materials so that they impact upon objects that are not optically visible from the radiating source [6]. By diffracting in the earth's atmosphere,

radio waves bend around the earth's surface and can travel far beyond the visible horizon. Also, due to diffraction, the effective height of any geological formation in the direct line-of-sight is reduced in its effectiveness at preventing direct LOS. The amount the effective height is reduced by the radius of the second Fresnel zone (the second Fresnel zone is considered in order to provide a more conservative, and realistic, approach toward modeling the varying characteristics of wind turbines) [5] of the transmitted radio waves. Thus, both an optical shielding point and a radar shielding point are obtained [7], though the radar shielding point is the only one of real interest.

Line-of-sight calculations are performed in the following section. If a wind turbine is deemed to be within radio LOS of the ATC Secondary Surveillance radar, its presence may have adverse effects on the radar's performance. Most notably, it may yield an increase in the radar's effective noise floor level due to reflection.

4.2 MSSR Line-of-Sight Distance

Through a simple mathematical model, it is possible to calculate a maximum LOS distance between the radar site and any wind turbines in its vicinity based on the curvature of the earth and the assumption of smooth terrain. That is, we are interested in establishing a minimum distance between the MSSR and any one wind turbine such that a radio signal transmitted from either location is not incident upon the other. The model detailed herein is based upon NTIA Technical Report TR-08-454 [8]. The figure below offers a basic diagram of the situation.

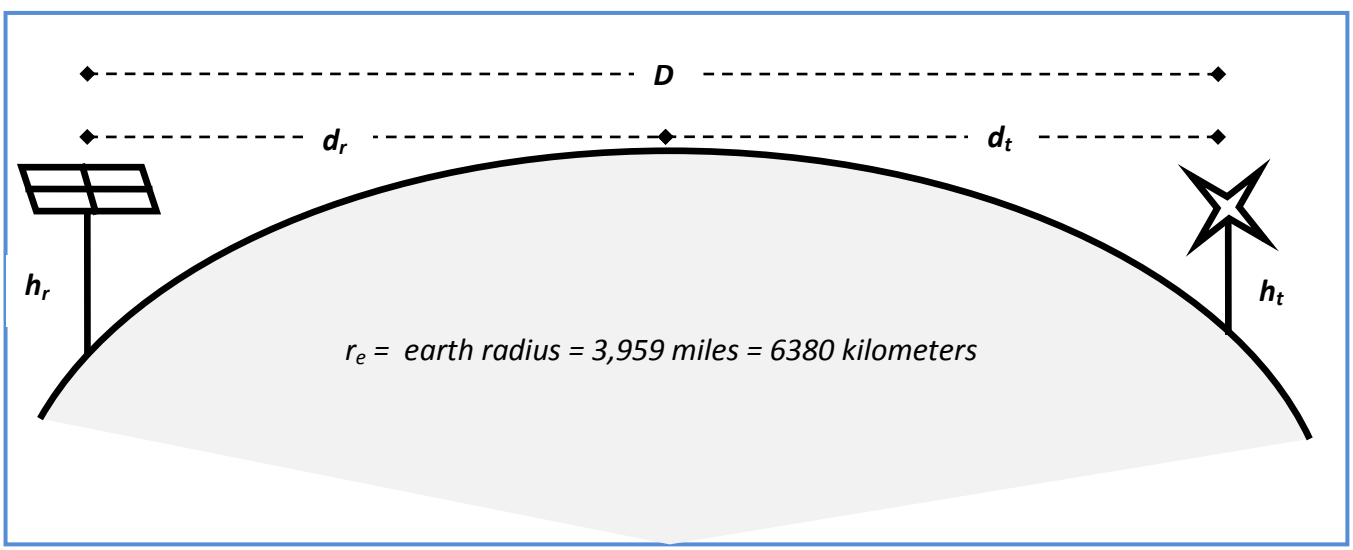

Figure 3: Minimum LOS model

where

D is the total distance between the ASR-11 radar and a wind turbine (mi)
d_r is the distance from the radar to the radio horizon (mi)
d_t is the distance from the wind turbine to the radio horizon (mi)
h_r is the height of the radar (ft)
h_t is the height of the wind turbine (ft)
r_e is the radius of the earth (mi)

In the calculation, one accounts for atmospheric diffraction effects by using the earth's effective radius, which is 4/3 times its actual (optical) earth radius in most circumstances. This factor accounts for the bending of radio signal in atmosphere, allowing them to travel greater distances than optical LOS. Thus, the distance between either of the objects and the horizon can be calculated using a simplified version of the Pythagorean Theorem:

$$d_r \approx \sqrt{2 * \frac{4}{3} r_e * h_r}$$

Equation 1

$$d_t \approx \sqrt{2 * \frac{4}{3} r_e * h_t}$$

The height of the MSSR antenna is 95 feet above mean sea level. Though the wind turbines vary in mean height above sea level, the tallest turbine is chosen for analysis because it will provide for a worst-case scenario; the tallest turbine is 451 feet above mean sea level. Combining the two distances, one solves for the overall minimum distance for non-LOS:

$$D = d_r + d_t = \sqrt{2 * \frac{4}{3}(5280 * 3959) * 95} + \sqrt{2 * \frac{4}{3}(5280 * 3959) * 451}$$

Equation 2

$$D = 2.31 * 10^5 ft = \mathbf{43.81\ mi} = \mathbf{38.1\ nmi}$$

Thus, assuming flat earth, 38.1 nautical mile boundary from the ATC radar has to be free of wind turbines to expect no adverse effects to the radar performance. However, this is not the case for the Riviera wind farm that all 75 turbines are to be in 9 to 11.5 nautical miles from the NASK ATC radar. The two figures below show the direct line-of-sight from the radar to the nearest (~9 nmi) and then furthest (~11.5 nmi) wind turbines. The LOS path is denoted by the straight green line with the blue ellipsoid representing the first Fresnel zone of the signal. The path profile figures below were generated in ATDI HTZ Warfare software.

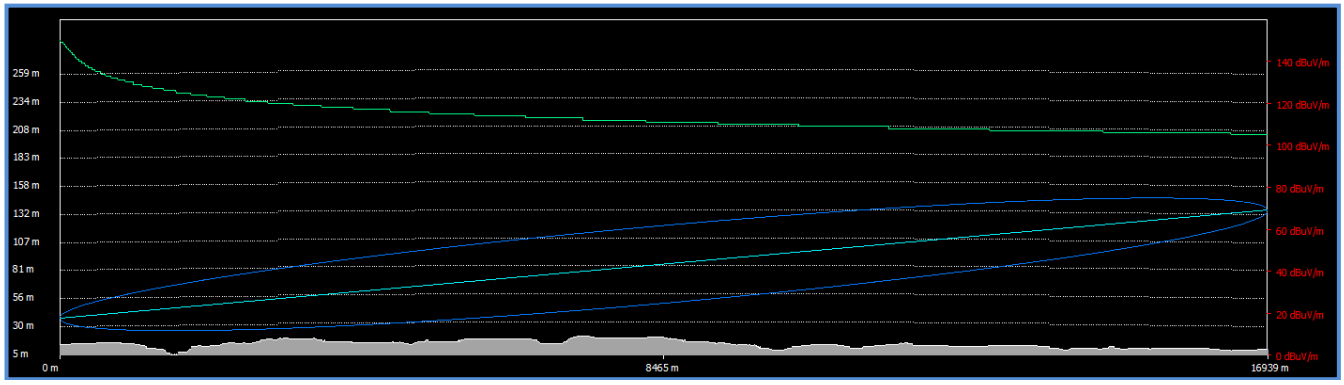

Figure 4: LOS from MSSR to nearest wind turbine (~9 nmi)

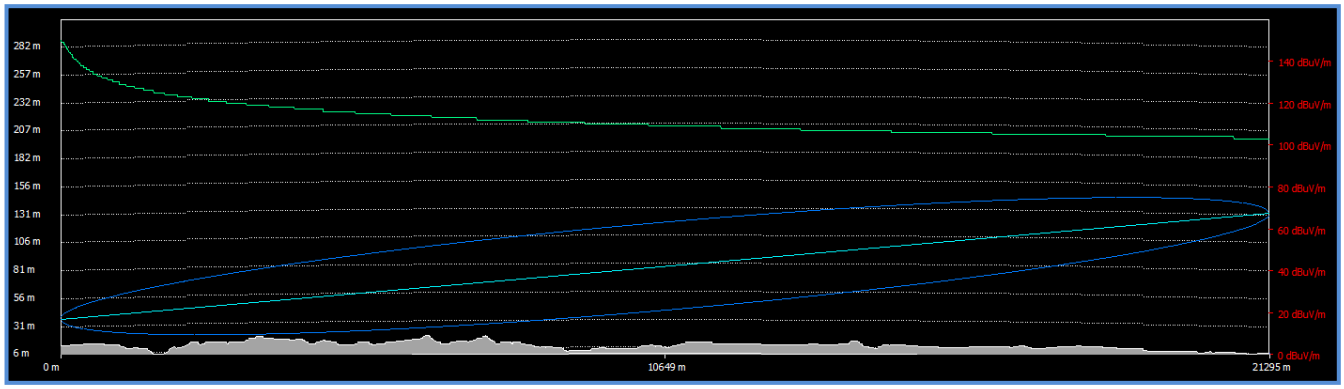

Figure 5: LOS from MSSR to furthest wind turbine (~11.5 nmi)

The turbine's tip of the blade at 125 m above ground level (AGL) can be in radio line-of-sight (RLOS) from the MSSR up to 16.2 nmi distance. Hence, there is a potential adverse effect from the Riviera wind farm, which is within the RLOS (9 to 12 nmi) from the MSSR leading to the next phase of the assessment; 3D shadow zone calculation.

Including the first Fresnel zone clearance and terrain data, the projected Riviera wind turbines are well within LOS of the MSSR where the LOS distance extends as much as up to 16.2 nmi from the MSSR site.

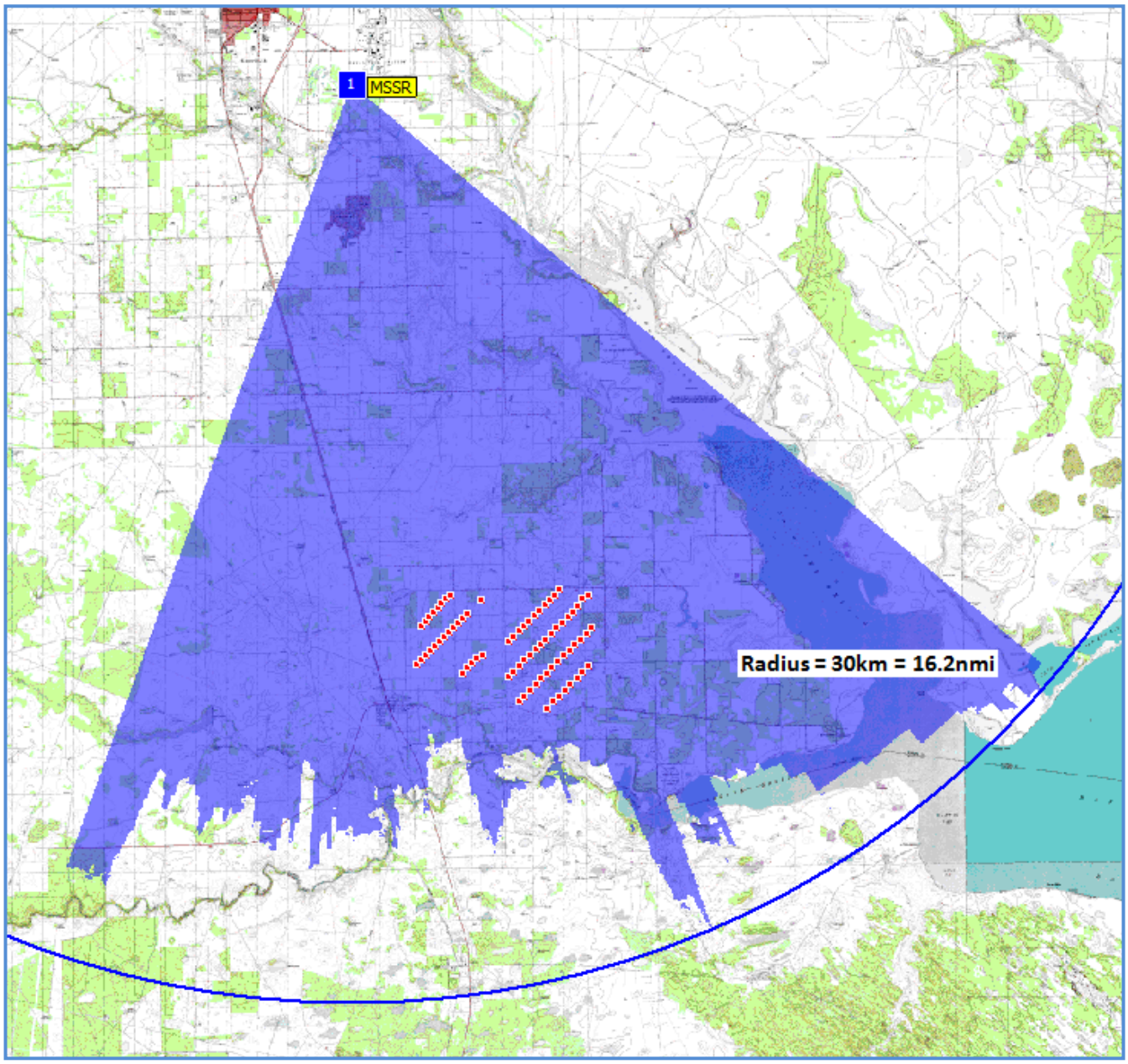

Figure 6: NASK MSSR LOS Coverage

5. 3D Shadow Zone Assessment

From the previous section, we identified that turbines would be located within the LOS of the MSSR, generating a shadow behind turbines; the effect of the shadow region degrades the performance of MSSR. In this section, we will analyze both the shadow region in three-dimension and maximum protection distance where the wind turbine reflected signal is likely to be detected by the aircraft transponder.

This computation is carried out by applying the NASK MSSR specific parameters, and by utilizing formulas provided in "EUROCONTROL Guidelines on How to Assess the Potential Impact of Wind Turbines on Surveillance Sensors", ref [17].

Line No.	Parameter	Value	Meaning
110	Frequency	M1030	1030 MHz
114	Emission Designator	9M00M1D	9 MHz
115	Transmit Power	W632	632 W
117	Effective Radiated Power	85	85 dBm
357	Transmit antenna Gain	27	27 dBi
457	Receive Antenna Gain	27	27 dBi

Table 1: NASK MSSR Parameters from SFAF Record

5.1 Shadow Length Calculation

First, we start with calculating the maximum distance that the aircraft is likely to detect the reflected signal. This protection range is calculated based on the transponder receive threshold that beyond this distance the reflected interrogation signal would dissipate to a level that is less than the sensitivity of the transponder.

$$D_{wr} = \sqrt{\frac{\sigma * F_{tw} * F_{wr} * G_{tw} * G_{wr} * P_t * \lambda^2}{(4\pi)^3 * D_{tw}^2 * P_{thresh}}}$$

Equation 3

P_t MSSR power (W)
G_{tw} Transmit antenna gain in the direction of the wind turbine
G_{rw} Receive antenna gain in the direction of the wind turbine
F_{tw} Attenuation due to terrain obstruction between transmitter and wind turbine
F_{wr} Attenuation due to terrain obstruction between wind turbine and receiver
D_{tw} Distance transmitter to wind turbine (m)

D_{wr} Distance wind turbine to receiver (m)
λ Signal wavelength (m)
σ RCS of the wind turbine (m^2)
P_{thresh} Transponder threshold

Based on the uncertainty of the factors involved in the RCS calculation and the suggestions found in pertinent literature, the value of 30 dBsm is assumed to provide a conservative estimate of a typical RCS value (e.g. the referenced literature, [17], applies 35 dBsm). For P_{thresh}, a value of -77 dBm is applied as it is a typical receive threshold for the transponder.

By applying the values of the MSSR from Table 1 and below, the computation follows:

P_t = 632 W
G_{tw} = $10^{-2.7}$
G_{rw} = 1
D_{tw} = 9 nmi ≈ 16,700 m
λ = 0.2913
σ = 1,000 m^2
P_{thresh} = $10^{-10.7}$
$F_{tw} = F_{wr} = 1$

$$D_{wr} = \sqrt{\frac{1000 * \ 501.2 * 632 * 0.2913^2}{(4\pi)^3 * 16700^2 * 10^{-10.7}}} = 1.56\ Km = 5{,}118\ ft$$

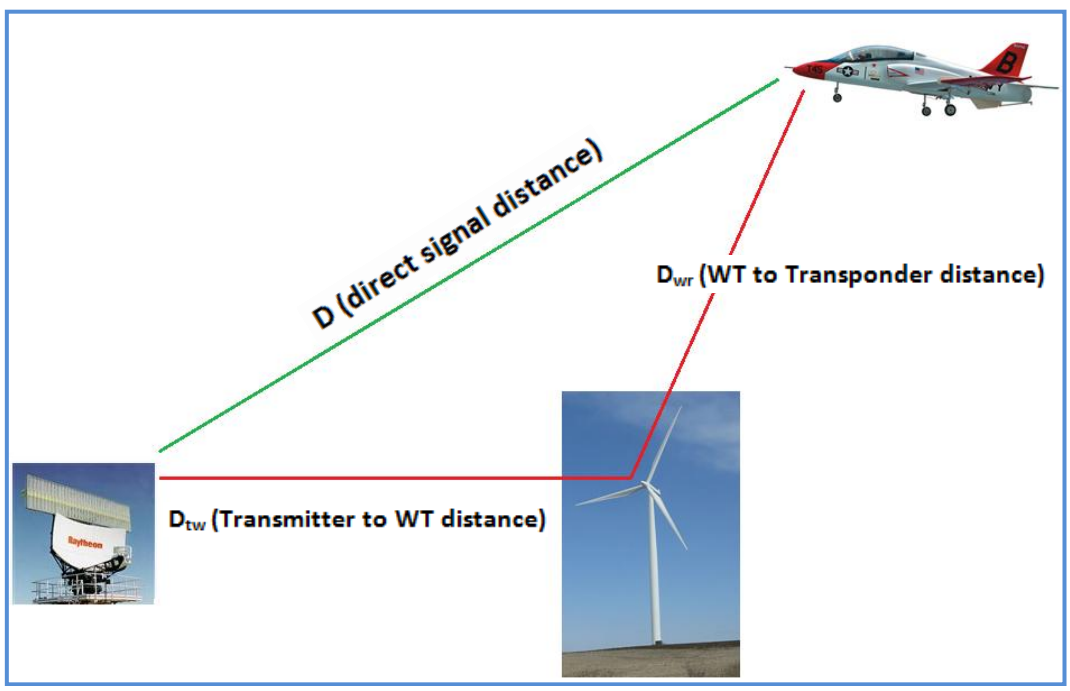

Figure 7: Direct and Indirect Signal Paths

5.2 Shadow Height and Width Calculation

The distance of D_{wr} from the previous section defines the length of the shadow region that the reflected signal can be detected by the aircraft up to the distance of 5,118 feet. Given that now we have calculated the length of the shadow, we need to compute the shadow height in consideration of the turbine height, the curvature of earth, earth radius by factor of 4/3 (K-factor). Below Figure 8, from reference [17], represents the principal of shadow height calculation.

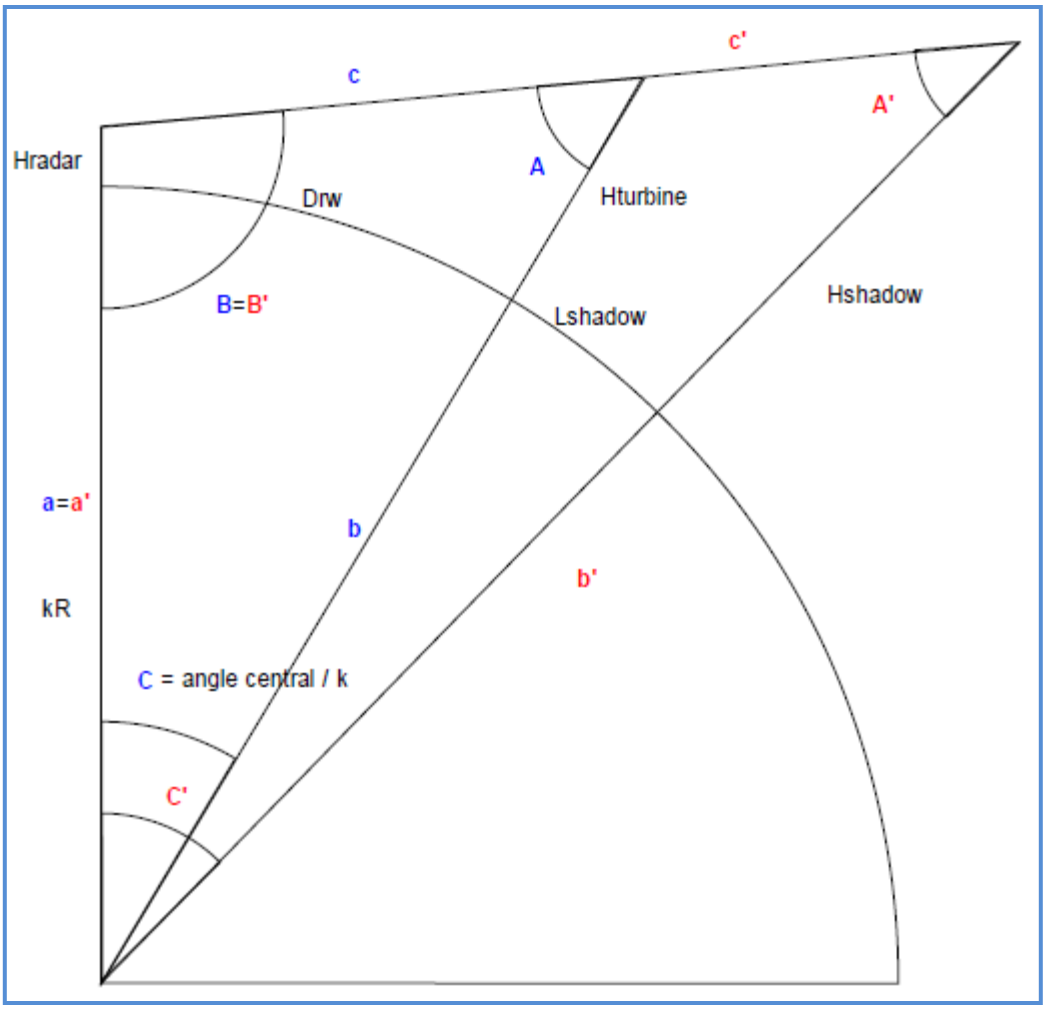

Figure 8: Geometry of MSSR and Wind Turbine

MSSR Antenna Height = 29 m AMSL
Tallest Turbine Height = 138 m AMSL
kR (effective earth radius) = $\frac{4}{3}\ (6371\ x\ 10^3)$ m

$$\boldsymbol{a = kR + H_{radar} = \frac{4}{3}\,(6371\ x\ 10^3) +\ 29 = 8,494,695.7}$$ **Equation 4**

$$b = kR + H_{turbine} = \frac{4}{3}\,(6371\ x\ 10^3) +\ 138 = 8{,}494{,}804.7 \quad (4.2)$$

$$C = \frac{D_{rw}}{kR} = \frac{16700}{kR} = 0.001966 \quad (4.3)$$

$$c = \sqrt{a^2 +\ b^2 -\ 2ab * \cos(C)} =\ 16{,}668.52 \quad (4.4)$$

$$B = Arccos\left(\frac{a^2 - b^2 + c^2}{2ac}\right) = 1.576355 \quad (4.5)$$

$$C' = \frac{D_{rw} + L_{shadow}}{kR} = 0.0021458 \quad (4.6)$$

$$A' =\ \pi - B - C' =\ \pi - 1.576355 - 0.0021458 = 1.56 \quad (4.7)$$

$$b' =\ a * \frac{\sin(B)}{\sin(A')} = 8{,}495{,}112 \quad (4.8)$$

$$H_{shadow} = b' -\ kR = 149.88\ meters =\ 491.73\ ft \quad (4.9)$$

As a final step in determining the three-dimension of the shadow zone, we use the following equation to calculate the width of the shadow:

$$\boldsymbol{W_{shadow} = \sqrt{\left(\lambda/_2 +\ D\right)^2 - D^2} = 72.9\ meters = 239.2\ ft}$$ **Equation 5**

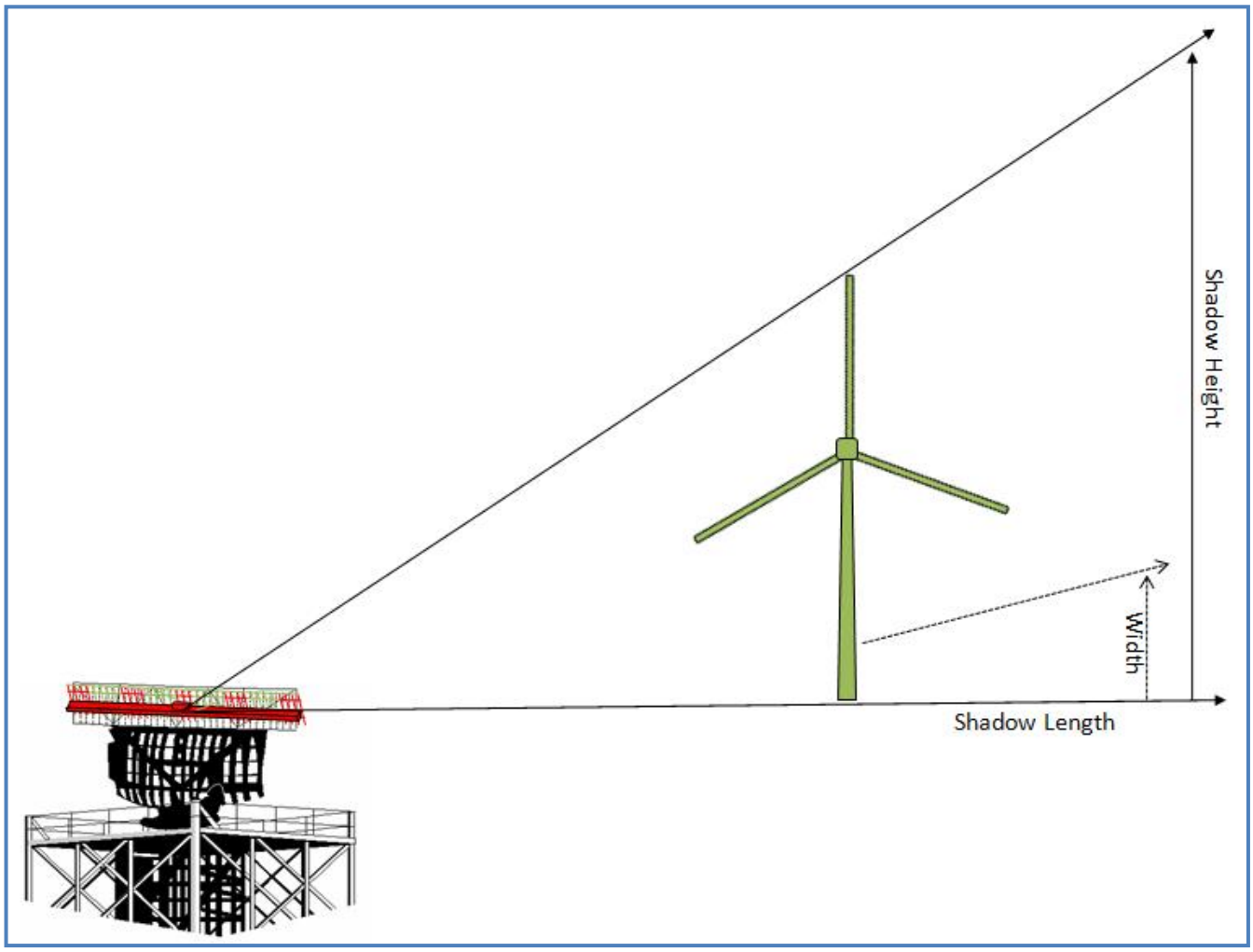

Figure 9: 3D Shadow Zone

1. **Hence, the calculations show that the potential three-dimensional shadow region behind a turbine is estimated to be 5,118 ft x 239 ft x 492 ft (L x W x H)**. If multiple wind turbines were located within the MSSR beam width, the size of the shadow zone would also increase accordingly. These three-dimensional shadows appear in the form of narrow wedges when viewed from both a top view and a side view, stretching beyond the blocking turbine. Targets of interest may be lost within such a shadow due to the reduced field strength of the radar signal since the full power of the transmitted signal does not penetrate beyond the blocking wind turbines. However, NASK provides the flight profile of 1,800 – 2,000 feet in the Riviera wind farm area, which eliminates the concern over the shadow effect.

5.3 Shadow Region Analysis on Hypothetical Wind Turbines

To analyze how close the wind turbines can exist from the MSSR and to assess shadow zone of hypothetical wind turbines located closer than the Riviera wind farm from the MSSR, calculations for turbines from 5 km to 16 km are performed in 1 km increment. The purpose of this analysis is to provide minimum flight altitude recommendation – if the type of the wind turbine is to be installed at other locations – to avoid being in shadow zone which could potentially degrade the MSSR detection probability.

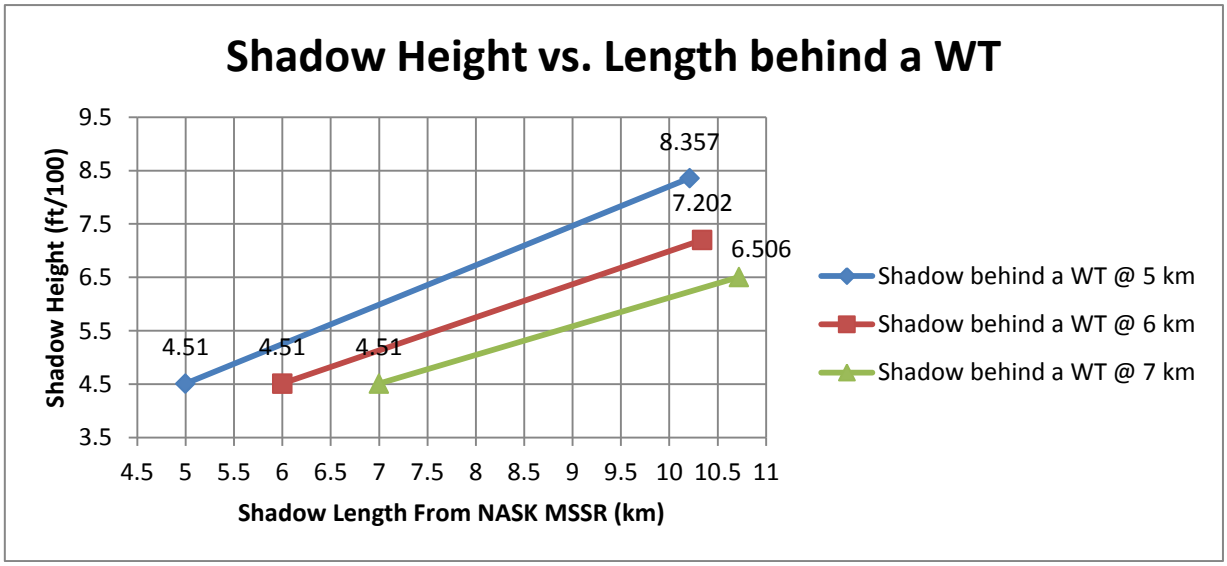

Figure 10: Shadow zone behind WTs located at 5, 6, and 7 km

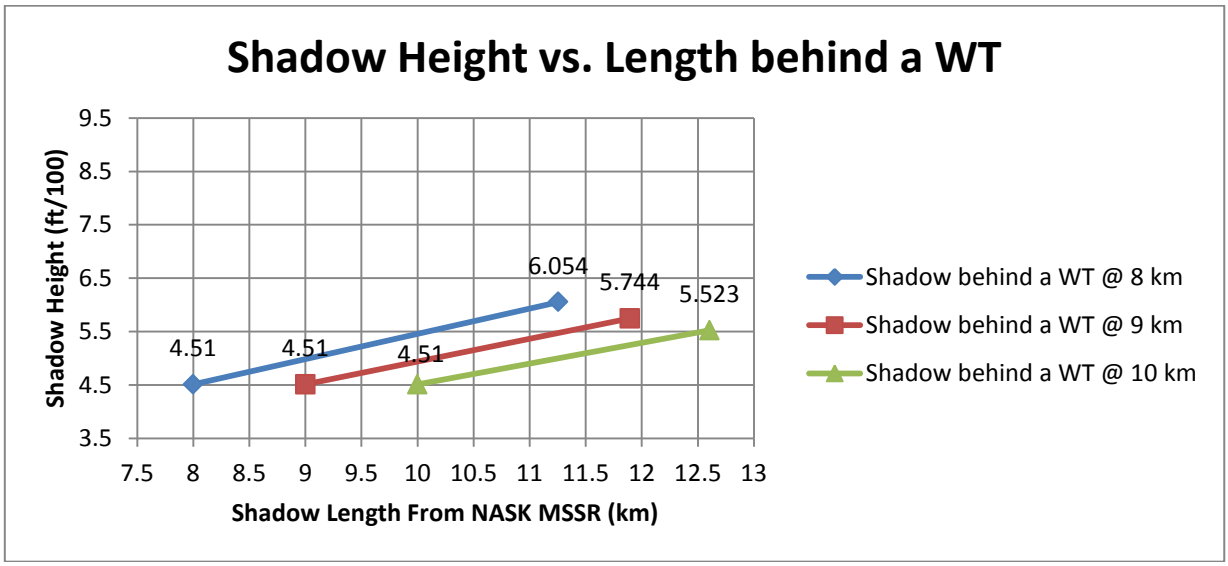

Figure 11: Shadow zone behind WTs located at 8, 9, and 10 km

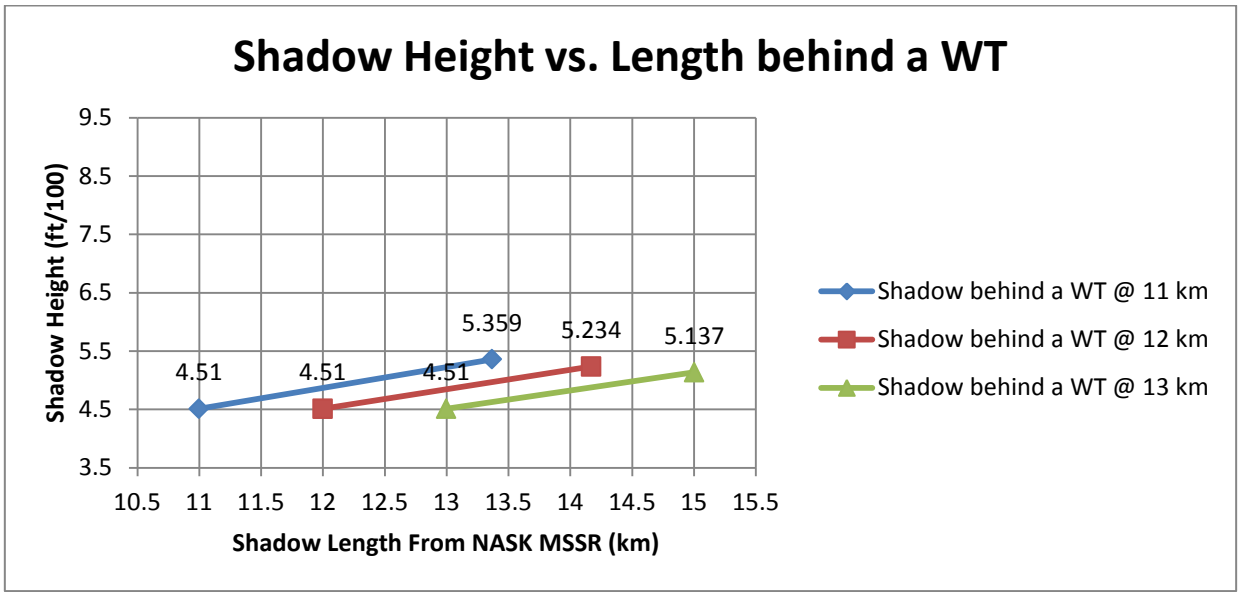

Figure 12: Shadow zone behind WTs located at 11, 12, and 13 km

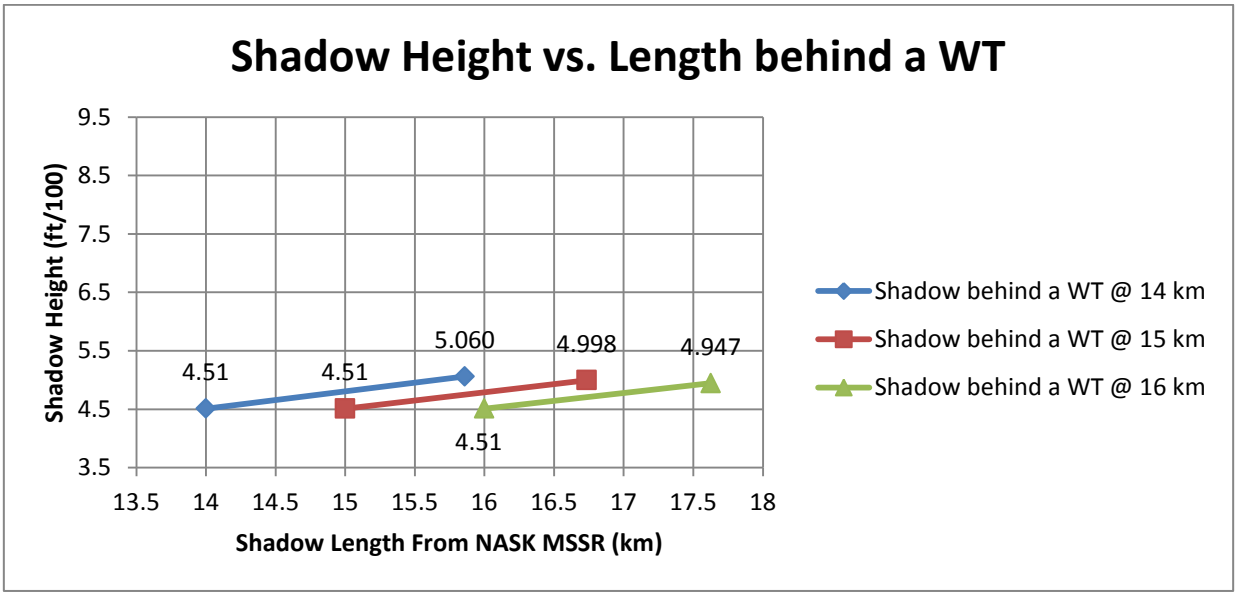

Figure 13: Shadow zone behind WTs located at 14, 15, and 16 km

6. False Target/Response Report

As a continuation of the signal reflection impact assessment based on three-dimensional shadow zone from the interrogation prospective, we will now consider false response phenomenon. Duplicated reply causing false target detection may occur due to a reply from a transponder when the interrogation signal happens to be reflected onto a wind turbine. However, within the distance of 5,250 meters (2.84 nmi), transponder will not reply to reflected interrogations by the implementation of Interrogator Side Lobe Suppression (ISLS). Because of the ISLS implementation, the transponder will be insensitive during a 35 µs period after the reception of a radar interrogation through radar sidelobes.

ISLS is used to resolve signal leakage problem that when the directional interrogation signals are transmitted, the signal may leak through the sidelobes. An aircraft receiving and responding to the sidelobe signal could cause interference on the channel. Hence, ISLS works by radiating an additional pulse, P2, to the transponder along with the first pulse P1. The transponder compares the two pulses and reply only if P1 is significantly stronger than P2. However, the signal level of P1 and P2 becomes approximately the same when the aircraft is closer; thus, the transponder is temporarily disabled for approximately 35 µs to prevent from replying to the leaked interrogation signal.

Therefore, any aircraft/transponder located closer than 5,250m (half of distance corresponding to 35 µs) will not reply to reflected interrogations because in this case the path difference between the direct and the reflected signal will always be smaller than 35 µs [17].

To avoid this phenomenon, a calculation is performed below to determine the minimum distance requirement between the MSSR and a wind turbine in **order to prevent the transponder replying to any reflected interrogation signal**.

The following values are used:

$P_{thresh} = 10^{-10.7}$ W

$P_t = 632$ W

$\sigma = 30$ dBsm = 1,000 m^2

$G_{tw} = 10^{2.7}$

$G_{wr} = 1$

$D_{wr} = 5{,}250$ m

$\lambda = 0.2913$ m

$F_{tw} = F_{wr} = 1$ (no terrain induced attenuation)

$$\boldsymbol{D_{tw}} = \sqrt{\frac{\boldsymbol{\sigma * F_{tw} * F_{wr} * G_{tw} * G_{wr} * P_t * \lambda^2}}{\boldsymbol{(4\pi)^3 * (D_{wr})^2 * P_{thresh}}}} \qquad \textbf{Equation 6}$$

$$D_{tw} = \sqrt{\frac{1000 \ * 10^{2.7} * \ 632 \ * \ 0.2913^2}{(4\pi)^3 * \ (5250)^2 * \ 10^{-10.7}}} = 4{,}963 \ m$$

Then D_{tw} = 4,963 meters = 2.68 nmi which the distance is less than the distance of the first wind turbine in the Riviera wind farm. Hence, for MSSR Mode A/C operation,

a) **If an aircraft is located less than 5,250 m from a wind turbine, the implementation of ISLS is applied; therefore, no reply to reflected interrogations,**
b) **If an aircraft is located further than 5,250 m from a wind turbine, the reflected interrogation signal level drops to below the transponder receiver threshold – 1,560 m maximum reflected interrogation signal propagation range (shadow length) was calculated from the previous section using Equation (1).**

Figure 14 below represents the 4,963 m radius circle from the MSSR as a wind turbine exclusion zone that a turbine installed within this zone would possibly cause significant interrogation signal reflection off the turbine, which may lead to false target detection due to the duplicated replies.

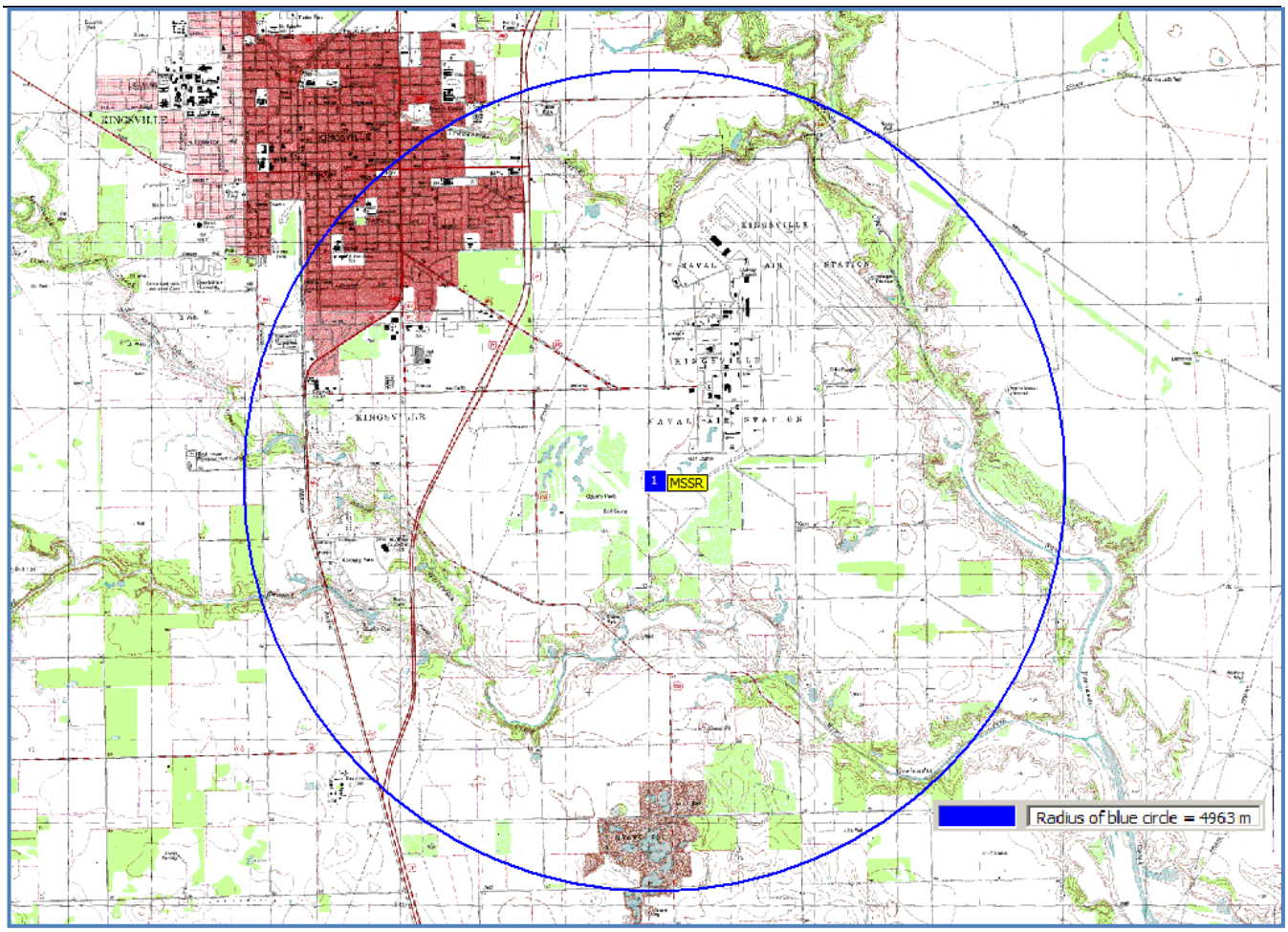

Figure 14: Wind turbine exclusion zone

The maximum interrogation-signal propagation distance of 5,118 ft is calculated in the shadow zone analysis. However, the MSSR's implementation of Interrogator Side Lobe Suppression (ISLS) technique minimizes this false target report phenomenon up to 17,224 ft (5,250 m); hence, no adverse effect is predicted for aircrafts flying closer than 17,224 ft from a turbine.

The three beams utilized by MSSR – sum, difference, and control – its function and capability are to minimize false target errors.

- The sum beam consists of a main lobe that typically has a gain of 24 dB or more above the sidelobes.
- The difference beam is used to provide improved direction finding. It works in conjunction with the sum beam. Many returns from the target are received as the main lobe of the sum

beam as the main beam sweeps across the target in azimuth. The target bearing is found by using the relative phase of the return in the two sides of the difference beam.

- The control beam has a gain that exceeds the gain of the sum beam in all directions except that of the main lobe. The control beam is used in conjunction with the sum beam to inhibit interrogation by the sidelobes which the technique is called sidelobe suppression.

Below figure displays the radiation pattern plot of sum, difference, and control beams from MSSR System manual provided by NASK.

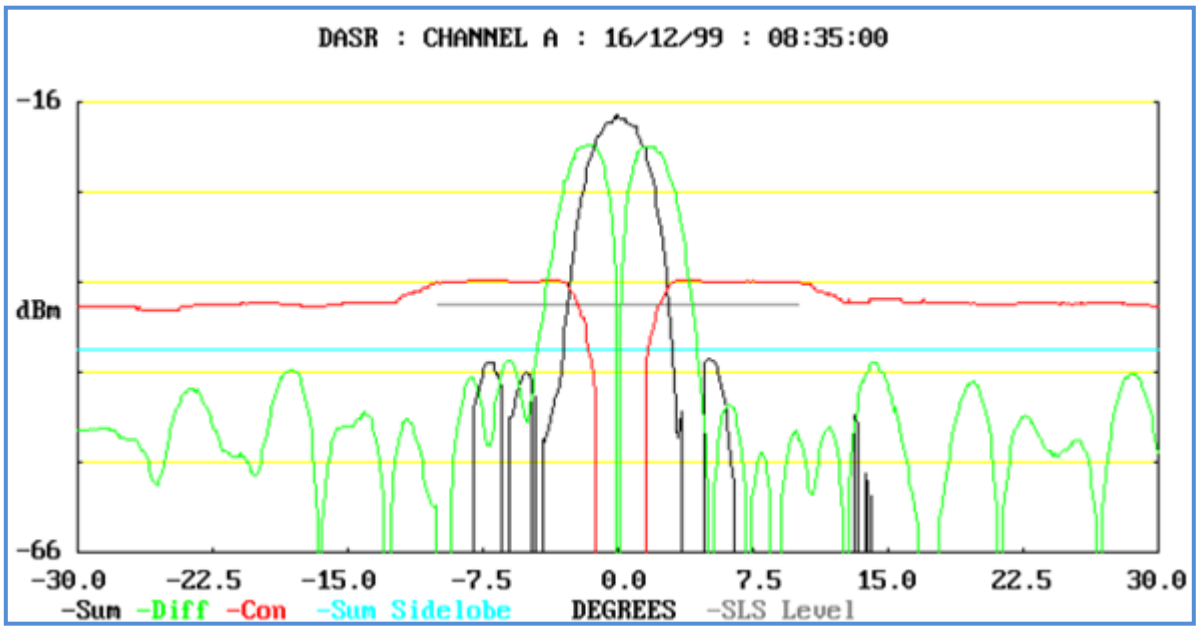

Figure 15: Antenna Pattern Measurement Plot

Aircraft/transponder replies are received by the two sum and difference beams and the azimuth estimation is a function of the ratio between the channels output of either amplitude or phase.

From the MSSR signal processing point of view, the MSSR receiver sensitivity is altered by adjusting the receiver gain based on the fact that the power at a receiver will be attenuated by 6 dB for every doubling of the range. This capability is called Sensitivity Time Control (STC).

Basically, the sensitivity is reduced as the range to the target reduces. According to Sym808390 – MSSR System manual, STC has three different settings:

1. OFF mode => Receiver at its maximum sensitivity throughout detection range.
2. Linear => Gives initial depression of sensitivity from zero range to first step. The sensitivity then increases at a selectable rate, normally 6 dB per doubling of range. This STC rule is applied identically to all azimuths.

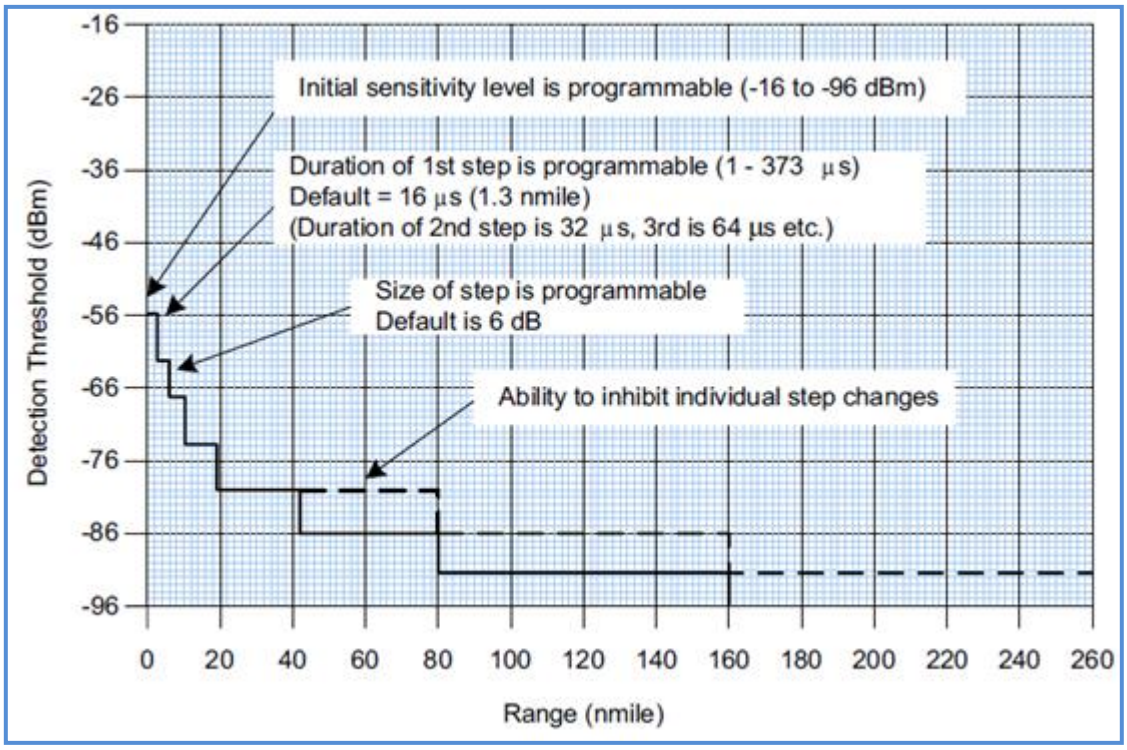

Figure 16: Linear STC Plot from Raytheon MSSR Sym808390 Manual

3. Programmed mode => An EPROM, which is located on the SSR and Mode S reply decoder PECs, allows different sensitivities to be programmed in azimuth sectors and ranges. There are 64 equal azimuth sectors and 1024 equal range cells in each azimuth sector. At most sites false target suppression requirements will be met by using Linear STC. However, some unique reflection conditions may require an increased threshold at a particular location where use of such a threshold would adversely affect performance if Linear STC were used at all azimuths. Similarly, a unique detection requirement, e.g. low level coverage at a nearby airport, may require a reduced STC threshold at a particular location.

7. Position Accuracy (Bearing Error)

The major improvements in mode-S are increased azimuth accuracy and its interrogation ability. Unlike other modes, mode-S interrogates one aircraft at a time therefore the workload on the aircraft transponder is reduced. On the other hand to increase position accuracy, mode-S can rely on information of one reply to determine the target azimuth where this determination is based on the RF phase of the aircraft reply by utilizing the sum and difference antenna beams as discussed previously.

Position accuracy is especially important with mode-S MSSR due to the fact that the interrogation only occurs at the previously recorded bearing for the target. If the bearing is incorrect, there is a chance that the aircraft/transponder would not be interrogated. An MSSR mode-S system calculates the bearing of an aircraft using the orientation of the EM wave as it reaches the antenna. **Reflections of the transponder signal from nearby objects (such as wind turbines) will combine with the direct signal in such a way that the wave-front is distorted [17] leading to degradation in position accuracy.**

Position error happens when the following two criteria are met:

1. When the difference between direct signal strength and the reflected signal strength is less than the system requirement,
2. When direct and reflected signals have a small path difference of < 75 meters.

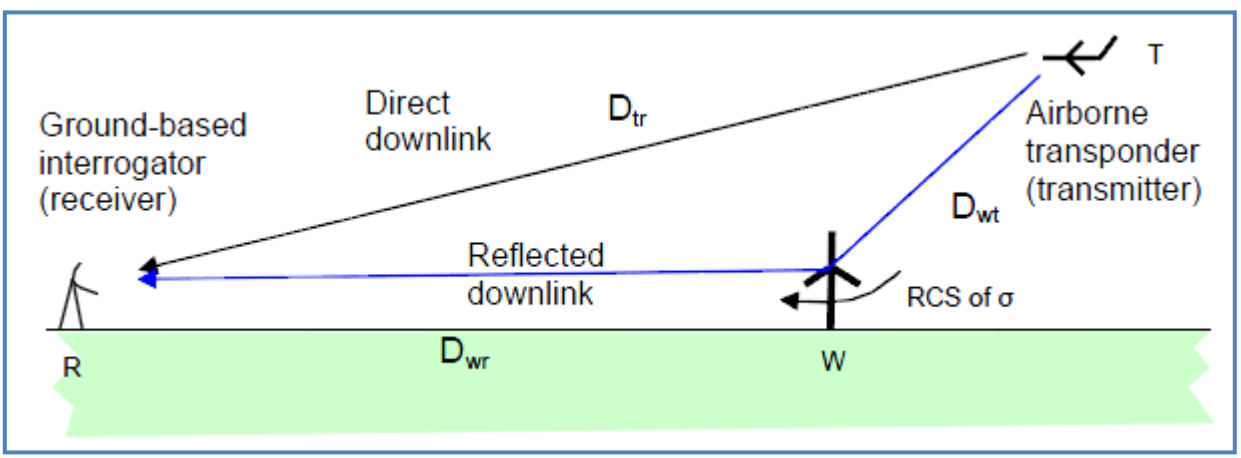

Figure 17: SSR Downlink Reflection, [17]

$$\frac{C}{I} = \frac{D_{tw}^2 * D_{wr}^2 * 4\pi}{D_{tr}^2 * \sigma}$$

Equation 7

where,

D_{tw} Distance from transponder (transmitter) to wind turbine
D_{wr} Distance from wind turbine to MSSR
D_{tr} Distance from transponder to MSSR
σ RCS of wind turbine

The above equation becomes

$$\frac{C}{I} \leq \frac{4\pi}{\sigma} * D_{wr}^2 \qquad \textbf{Equation 8}$$

as $D_{tw} \leq D_{tr}$.

The variable D_{wr} is 16.7 km for the closest wind turbine in the projected Riviera wind farm where the furthest wind turbine is 21.3 km from the MSSR.

Hence, by inputting these values,

$$\frac{C}{I}\ (dB) = 10 * Log\left(\frac{4\pi}{1000} * 16700^2\right) = 65.5\ dB$$

for the closest wind turbine.

$$\frac{C}{I}\ (dB) = 10 * Log\left(\frac{4\pi}{1000} * 21300^2\right) = 67.6\ dB$$

for the furthest wind turbine.

Now, the MSSR receiver sensitivity is calculated to derive the required C/I (*required "direct reply-signal level" above "wind turbine reflected signal"*).

To start out, the thermal noise level equation is:

$$\boldsymbol{Nf\ (dBm) = -174 + 10 * \log(B_{IF}) + NF} \qquad \textbf{Equation 9}$$

where

N_f is the noise floor in dBm
B_{IF} is the IF bandwidth of the MSSR in Hz
N_f is the noise figure in dB

The MSSR IF bandwidth is 9 MHz given from Table 1, and the noise figure is assumed to be 5 dB, which could range from 4 to 12 dB; therefore,

$$Nf\ (dBm) = -174 + 10 * \log(9 * 10^6) + 5 = -99.5\ dBm.$$

Hence, the calculated SNR (Signal-to-Noise Ratio) criterion for the MSSR is **16.5 dB (≈ 17 dB)** with the MSSR Rx sensitivity of -83 dBm provided by NASK. Therefore, C/I margins greater than 17 dB ensures a good discrimination between the direct and the wind turbine reflected signal that the previously calculated C/I values over 65 dB provides enough discrimination – the higher the margin, the higher the reliability preventing code corruption.

This bearing error phenomenon is referred to as Split Plots in the Raytheon MSSR manual which also includes code corruption and leading to high confidence code error. Additional losses in the reflected path will normally result in longer range multipath replies being of lower amplitude than the real reply. This fact may be used in the reply detection process to suppress such replies. STC may be sufficient, but there is also specific processing tailored for multipath. Use of LVA antenna has significantly reduced the impact of multipath on azimuth accuracy. Where such multipath is still present, small adjustment of the antenna tilt can reduce the amplitude of the reflected path. However, care should be exercised as antenna tilt can significantly affect long-range performance. [18]

8. Conclusion

Wind turbines are large moving objects with its variation in blade velocity and directivity based upon wind speed and direction, respectively. Moreover, the structure of the stationary part adds another factor due to its height causing shadows in extended areas. Seventy five (75) projected wind turbines to be built for the Riviera Wind Farm. Each turbine consisting of a 90 m rotor diameter, 80 m hub height, and 1.8 MW rated generator. The wind farm will be located south of NASK between 9 nmi and 11.5 nmi from the MSSR location.

Wind turbines can affect the propagation of electromagnetic energy from an MSSR to an aircraft, or vice versa. The potential impact of the wind turbines to an electromagnetic emission depends on a number of factors such as the wind turbine radar-cross-section (RCS), the terrain, and the position and altitude of the radar including its technical parameters. An in-depth analysis was undertaken to understand the impact of wind turbines on electromagnetic emissions. The analysis was based on the guidelines provided in "Guidelines on How to Assess the Potential Impact of Wind Turbines on Surveillance Sensors" by the European Organisation for the Safety of Air Navigation.

Four different scenarios were studied:

1. **Line-of-Sight** calculation is used to determine potential shadow effect produced from the turbine on the MSSR electromagnetic signal.

2. A **3D Shadow zone** is calculated that appears behind the turbine. The probability of detection is subject to degradation on low-flying targets when their altitude is less than 491.73 ft based on the calculation.

3. **False target report** analysis is performed in order to assess any potential issue of the aircraft/transponder replying to a 'turbine-reflected' interrogation signal. The resulting rationale for Mode A/C operations is

    a) If an aircraft is located less than 5,250 m from a wind turbine, the implementation of ISLS (Interrogator Side Lobe Suppression) is applied; therefore, there is no reply to reflected interrogations;
    b) If an aircraft is further than 5,250 m, the reflected interrogation signal level drops to below the transponder receiver threshold given that the maximum interrogation signal propagation distance is 1,560 m as calculated during the shadow zone analysis.

4. **Position accuracy** is especially important with mode-S MSSR because the interrogation only occurs at the previously recorded bearing for the target. There is a chance that the aircraft/transponder is not interrogated if the bearing is incorrect. When the difference between direct signal strength (C) and the reflected signal strength (I) is less than the system

requirement, the position error can occur. In this study, the calculated C/I margin is greater than 65 dB, which is a high enough margin to prevent possible code corruption.

The MSSR system implements many different advanced techniques to mitigate different cases of multipath phenomena. The mechanism and likely effect of the multipath cases are as follows:

	Angular Separation Between Direct and Reflected Paths		
	In Line (zero angle)	**Beamwidth** (small angle)	**Large Angle**
Short Path Difference (substantial overlap between same pulses arriving by two paths)	Vertical Lobing Fades	Beamshape Distortion Bearing errors Split Plots	Reflections
Long Path Difference (little or no overlap between pulses)	Code Corruption	Code Corruption Bearing Errors	Reflections

Table 2: Multipath Effects, [18]

Details of the MSSR mitigation technique includes:

- Code corruption may result in split plots (position accuracy) leading to the generation of false targets. However, in MSSR, processing within the reply correlation process has been designed to reject erroneous replies and combine split SSR plots.

- In addition, corrupted Mode-S replies will not result in false targets as they will be detected by the CRC process which allows error correction or re-interrogation if the reply cannot be corrected.

- STC, discussed in Chapter 6, can also be configured to discriminate against FRUIT replies that are lower amplitude than what would be expected for their received range.

- Use of LVA antenna can significantly reduce the impact of multipath on azimuth accuracy. Where small adjustment, with care of detection range performance, of the antenna tilt can reduce the amplitude of the reflected path.

- Use of Ray tracing technique to determine the location and orientation of the reflecting surfaces. Information of these surfaces is stored in reflector files in two types: permanent and self-adaptive. The self-adaptive processing system analyzes the geometry of real and false targets to calculate the position and orientation of the reflecting surface and enter it into the self-adaptive, or dynamic, reflector file. The processing provides for storage of the position and orientation of up to 64 permanent reflectors and up to 64 self-adaptive reflectors. [18]

- ISLS is used to resolve signal leakage problem that when the directional interrogation signals are transmitted, the signal may leak through the sidelobes. An aircraft receiving and responding to the sidelobe signal could cause interference on the channel. Hence, ISLS works by radiating an additional pulse, P2, to the transponder along with the first pulse P1. The transponder compares the two pulses and reply only if P1 is significantly stronger than P2. However, the signal level of P1 and P2 becomes approximately the same when the aircraft is closer; thus, the transponder is temporarily disabled for approximately 35 µs to prevent from replying to the leaked interrogation signal.

- The figure below shows reflection suppression processing and the data flow.

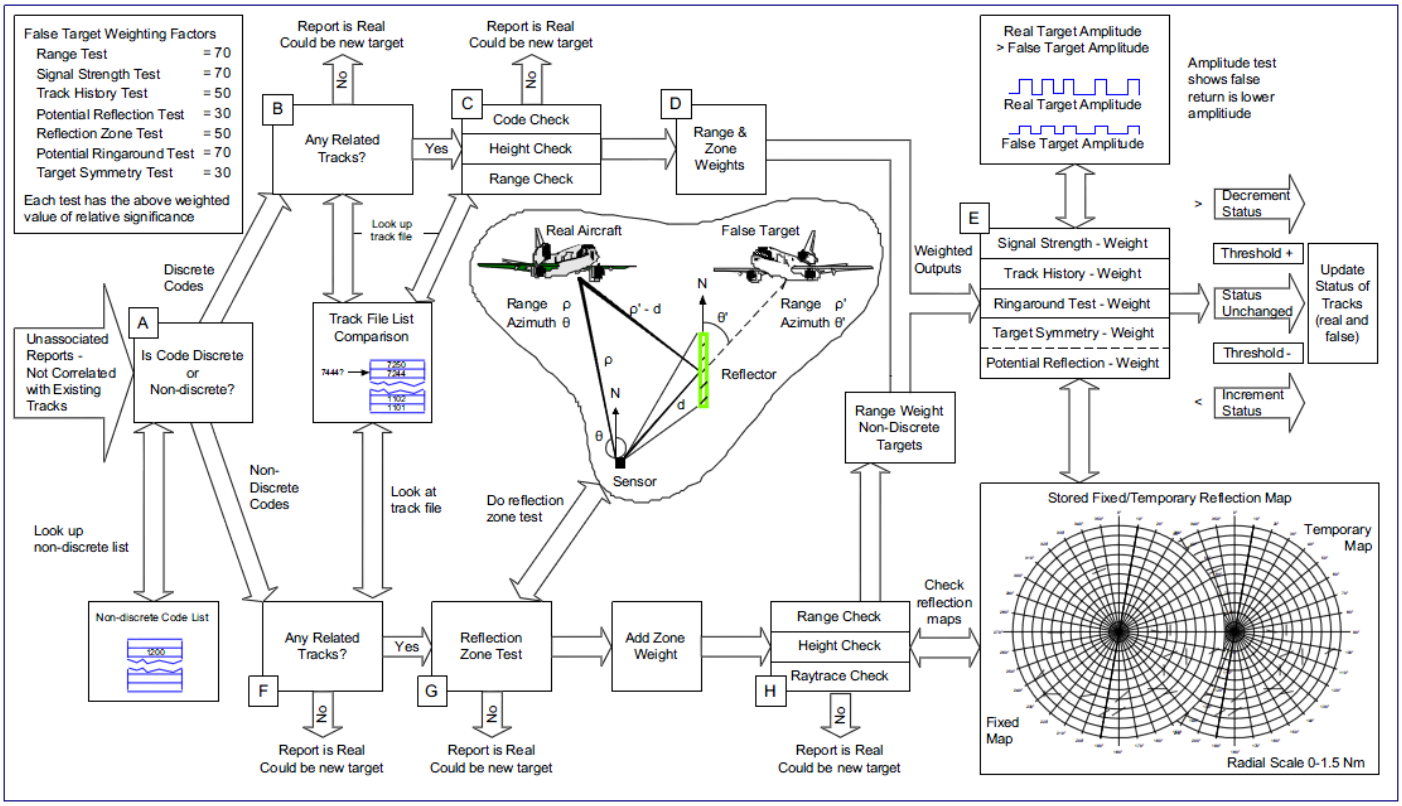

Figure 18: False Target Elimination, [18]

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10. Appendix—Summary of Cumulative Effects

This appendix, based upon content from Eurocontrol's 'Guidelines on How to Assess the Potential Impact of Wind Turbines on Surveillance Sensors' [17], is a broad look at the cumulative effects that are possible based upon the three types of negative effects that wind turbines may cause to MSSR when they are deemed to be in radar line-of-sight: shadowing, multiple target reports, and azimuth accuracy.

Shadow Volumes

As calculated earlier in this report, the shadow 'cast' by a typical single wind turbine is 5,118 feet in length, 239 feet in width, and 492 feet in height. The volume of this shadow region is:

$$V_{shadow} = L * W * H = 5118 * 239 * 492 = 6.018 * 10^8\ ft^3$$

Of interest is the fraction of MSSR scanned volume that a group of wind turbines (a wind farm) may occupy. The elevation pattern of a typical MSSR antenna has the majority of its gain located between 0° and 15° above horizontal. It is assumed that this is the scanned volume of interest. Furthermore, the volume of interest extends out to 12 nautical miles from the location of the MSSR antenna; the entirety of the proposed Riviera Wind Farm would thus be located within the area of interest. Flat earth is assumed.

The scanned volume of interest is defined by the volume of an inverted cone subtracted from the volume of a disk:

$$V_{MSSR} = \pi r^2 h - \frac{1}{3}\pi r^2 h = \frac{2}{3}\pi r^2 h$$

$$V_{MSSR} = \frac{2}{3} * \pi * 72{,}913^2 * (72{,}913 * \tan 15°)$$

$$V_{MSSR} = 2.175 * 10^{14}\ ft^3$$

Thus, the total shadow volume 'cast' by the proposed 75-turbine Riviera wind farm compared to the overall volume of interest is:

$$\%_{shadow} = \frac{(\#\ wind\ turbines) * V_{shadow}}{V_{MSSR}} = \frac{75 * 6.018 * 10^8}{2.175 * 10^{14}} = .02\%$$

The equation presented directly above is linear and directly proportional. Barring the occurrence of overlap between shadow volumes and complete visibility of the wind turbines, the total shadow volume created by a wind farm is directly proportional to the number of wind turbines present. Using

the same methodology, the following percentages of the scanned volume of interest would be part of the shadow volumes created by wind turbines:

Table 3: Total volume versus shadow volume

Number wind turbines	Percentage of MSSR scanned volume of interest
50	0.014%
75	0.021%
100	0.028%
200	0.055%
500	0.140%
1000	0.280%

Multiple Target Reports

As discussed in the report, a narrow volume exists for the appearance to multiple targets. For a multiple target report to potentially occur, the distance between the MSSR antenna and the wind turbine must be less than 16 kilometers (8.6 nautical miles), the distance between the wind turbine and the aircraft must be greater than 5.25 kilometers (2.8 nautical miles) but small enough so that the reflected energy can still overcome the power threshold of the airborne receiver, and the wind turbine and aircraft must be within the main beam of the MSSR. This case is presented in the figure below, where the narrow arch represents the volume where potential multiple target reports may occur. The figure is a 2D 'cut'.

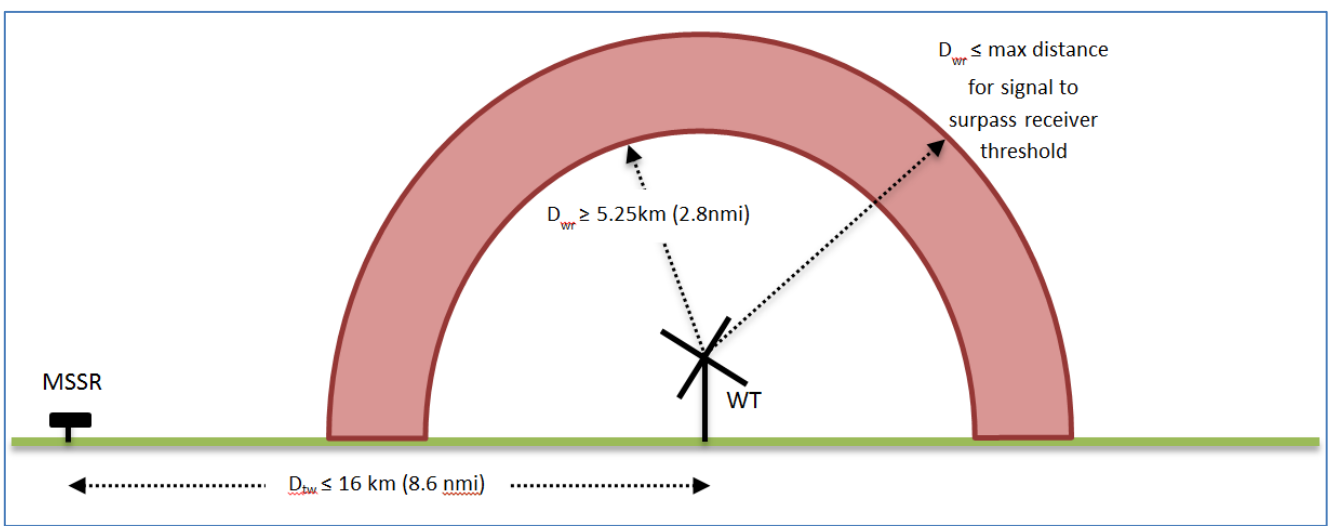

Figure 19: 2D representation of volume of potential multiple target reports

As can be interpreted from the figure, all three objects of interest must be aligned in a line. The wind turbine and plane must be within the main beam of the MSSR for this effect to take place. The

cumulative effect of the summation of the volumes of potential multiple target reports is demonstrated in the figure below. The narrow wedges appear as arches and are centered about wind turbines, as seen in the figure above. They are also limited in altitude, dependent on the distances that exist between the various objects under consideration.

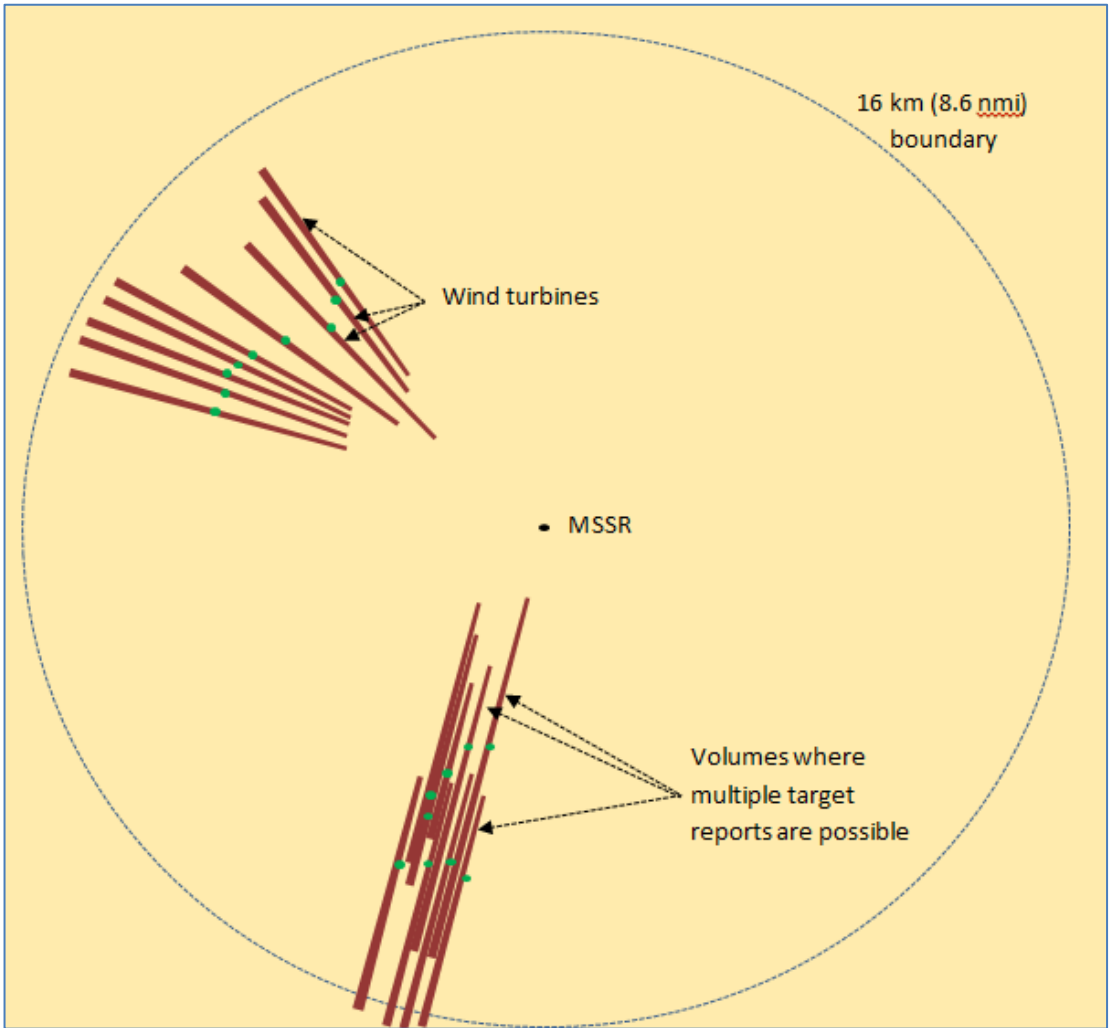

Figure 20: Sum of volumes where multiple target reports are possible

Azimuth Accuracy

Azimuth accuracy of the MSSR system is only affected by single turbines when the path difference between a direct signal and one reflected by a wind turbine is less than 75 meters (approximately 250 feet). This means that an airplane would have to be in the direct vicinity of a wind turbine, probably no more than several hundred feet away from it, for the possibility of an error in azimuth accuracy of an aircraft's position. Due to the spacing requirements for wind turbines, an aircraft cannot be close enough to two or more turbines to be impacted by them at the same point in time. Thus, a cumulative effect for azimuth accuracy is not expected.