ISTANBUL TECHNICAL UNIVERSITY ★ INFORMATICS INSTITUTE

SCATTER AND DOPPLER EFFECTS OF WIND POWER PLANTS TO LAND RADARS

M.Sc. THESIS

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Department of Communication Systems

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ BİLİŞİM ENSTİTÜSÜ

RÜZGAR ENERJİ SANTRALLERİNİN KARA RADARLARINA OLAN SAÇICI VE DOPPLER ETKİSİ

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Derya Sözen, a **M.Sc.** student of ITU **Informatics Institute** student ID **705081016,** successfully defended the **thesis** entitled "**SCATTER AND DOPPLER EFFECTS OF WIND POWER PLANTS ON LAND RADARS**", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family and TENTENA,

FOREWORD

I thank to my master thesis Supervisor Assoc. Prof. Dr. Mesut Kartal for his belief in me and my work, and also my parent for their infinite support. I also wanted to thank to my team leader Fırat Varlı for his patience. Finally, my special thanks go to Anıl Esen and Engin Karakuzu for inspiring me.

May 2012

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(Computer Engineer)

TABLE OF CONTENTS

Page

ABBREVIATIONS

AGI : Analytical Graphics, Inc.
AM : Amplitude Modulated
dB : Decibel
FM : Frequency Modulated
Hz : Hertz
I/N : Interference to Noise ratio
IEEE : Institute of Electrical and Electronics
LOS : Line of Sight
MATLAB : Matrix Laboratory
MKS : Meters, Kilograms and Seconds
MTI : Moving Target Indication
PD : Pulsed Doppler
RADAR : Radio Detection And Ranging
RCS : Radar Cross Section
RF : Radio Frequency
rpm : Rounds per minute
S/N : Signal to Noise Ratio
STK : Satellite Tool Kit
TIREM : Terrain Integrated Rough Earth Model
W : Watts

LIST OF TABLES

Page

LIST OF FIGURES

Page

SCATTER AND DOPPLER EFFECTS OF WIND POWER PLANTS ON LAND RADARS

SUMMARY

Wind power plant installations at different scales are in an increasing pattern starting from year 2000. A curiosity has been raised about 4-5 years ago for if wind turbines interfere with radars. So angular tracking of two closely spaced radar targets, in our case wind turbine blades are considered in order to cancel out their effects. The interference occurs when wind turbines reflect radar waves and cause missing targets and blind regions on radar images. Doppler radars are most used to discriminate between the return from a desired target and that from undesired objects, usually ground clutter.

Radar energy can be lost in two main ways: by being absorbed into a material, that converts it into another form of energy and by destructive interference. Studies, have shown that the rotating blades and support structure of a wind turbine can impact AM RF signals. FM signals are much more immune to this phenomena and may only become impaired in very close proximity to a wind turbine. AM radio antenna systems are sensitive to any tall structures made of conductive material. Reradiation from steel turbine support structures can modify the radiation patterns of AM stations and cause interference to other stations.

Telemetry transmission was recently explored as a potentially cheap and easy option. Real-time data could be fed into a model which could then predict the RCS of the wind farm and account for it in its displays, effectively removing the interference problem. While this seems like a daunting challenge, its proponents maintain it would be relatively simple, requiring four sensors on each turbine, continuously transmitting information on speed, location, pitch and yaw to the radar. Altogether this would consist of just a few hundred bytes of data per second. It is not clear at the present time if this is one of the technologies being taken forward.

There are so many resulting effects of interference such as shadowing, damage to radar equipment, larger RCS and missing desired targets, etc. Both radar and wind power plant mitigations are available. But still, there is no overall solution, only case by case treatment. RADAR will be used as “radar” throughout this paper.

RÜZGAR ENERJİ SANTRALLERİNİN KARA RADARLARINA OLAN SAÇICI VE DOPPLER ETKİSİ

ÖZET

2000’li yıllardan bu yana rüzgâr enerji santrallerine olan ilgi artmış bulunmaktadır. Farklı ölçeklerde çeşitli santrallerin inşası başlatılmış ve sayıları artarak devam etmektedir. Yaklaşık 4-5 yıl önce rüzgâr türbinlerinin çevresindeki radar istasyonlarına etkisi olup olmadığı merak konusu olmuştur. Bunun üzerine rüzgâr türbinlerinin açısal hareketleri incelenmeye başlanmıştır. Amaç etkinin tespit edilip çeşitli çözüm yollarının üretilmesidir. Türbinler radarın görüş açısında bulunuyorsa iki türlü etki edebilir ya radar dalgalarını geri yansıtarak yanıltıcı hedef bilgisi oluşturabilir ya da radar için çeşitli kör noktalar oluşturabilir. Doppler radarları bu durumda türbinleri gerçek hedeflerden ayırabilecek en donanımlı tip radarlardandır. Daha detaylı incelendiğinde rüzgar enerji santrallerinin gölgeleme, radar ekipmanına zarar verme, radar yansıtma yüzeyinin artması, kayıp hedefler ve bunun gibi pek çok etkisi vardır radarlara. Hem radar açısından hem de rüzgâr enerji santralleri açısından durumu iyileştirmek ve çözmek için pek çok yöntem mevcuttur.

En çok etkilenen radar tipleri savunma, meteoroloji ve trafik kontrol radarlarıdır. Rüzgâr türbinlerinin bıçak hareketlerinin radarlar üzerindeki etkisinin modellenebilmesi için çeşitli yöntemler vardır. Bu etkinin büyüklüğünü ve doppler kaymasını doğru canlandırabilmek edebilmek doğru çözüm aksiyonlarını alabilmek adına önemlidir. Rüzgâr enerji santrallerinin radarlara olan etkisi türbin sayısının artmasının yanı sıra daha büyük ve uzun türbinlerin kullanılmasıyla da artmaktadır. Bu sebepten türbinler daha uzak mesafelerden de radarları etkileyebilmektedir. Türbin bıçakları hareketli parçalar olduğu için gerçek hava olaylarıyla kolaylıkla karıştırılabilir radar datalarınında. Türbin bıçaklarının harekeleri binalar gibi sabit gürültü kaynakları olmadığı için, radarlardaki standart gürültü temizleme yöntemleri işe kullanılamaz. Radar gürültüsü zeminden yansıyan istenmeyen ekoların tümüdür. Doppler radar tasarlayan birinin en çok dikkat etmesi gereken bu ekoları ayırt edip

temizleyebilmektir. Etkili ve verimli bir radar tasarlayabilmek için bu tip bir gürültünün tanınması ve davranışının bilinmesi gerekmektedir. Bir cismin radardaki görünürlüğü radar kesit alanı arttıkça yükselmektedir. Radar kesit alanı hedefin şekline ve hareketine göre değişmektedir. Bir radarın performansı ne kadar uzaklığı görebildiği (range), ne kadar hedefin pozisyonunu tanımlayabildiği (accuracy), birbirine yakın cisimleri ne kadar iyi birbirinden ayırt edebildiği (resolution) ve arka plana sahip cisimleri ne kadar iyi görebildiğiyle (clutter improvement) ölçülebilir. Rüzgâr türbinlerinin radarların performanslarına olan bu tip etkileri dünya çapınca çok çeşitli projelerle ele alınmış ve incelenmiştir, ta ki sorun tanımlanıp çözüm yöntemlerine üretilmeye başlanıncaya kadar.

Bilgisayarların yaptığı iş, hedeften yansıyarak dönen dalganın gücünü, ne kadar sürede hedefe ulaştığı ve döndüğünü ve doppler kaymasını hesaplamaktır. Hedefin hızı ve yansıtma gücü radarın okuduğu ana iki bilgidir. Hedeften yansıyarak geri dönen dalganın gücü hedefin yansıtma gücünü gösterir. Hedeften yansıyarak dönen gücün doppler kayması ise hız bilgisini oluşturur. Frekanstaki değişim ise doppler frekansını gösterir. Eğer hedef vericiye yaklaşıyorsa doppler değeri orijinal frekans değerine eklenir, uzaklaşıyorsa çıkarılır. Ana hedeften radara dönen mikrodalgalar radara yaklaşan ya da radardan uzaklaşan bir yüzeye çarptıklarında dalga boyları değişir. Rüzgar türbinlerinin kanatları radara doğru dönüyorlarsa artı doppler kayması, radarın zıt yönüne doğru dönüyorlarsa eksi doppler kayması yaratırlar.

Rüzgâr enerji santrallerinde enerji üretmek için birden fazla rüzgar türbini bulunur. Bu santraller hem nokta gürültüsü hem de doppler kayması yaratan yapılardır. Radar vericisinden yayılan mikrodalgaların çoğu türbinlerin sabit parçalarından yansır. Türbinin gövdesini oluşturan sabit parçaların köşe yansımaları, düz alanları ve eğimli kenarları, hepsi radar kesit alanında hesaplanarak tespit edilebilir. Tespit edilen bu değer nokta gürültü değeridir. Rüzgâr türbinlerinin bir diğer özelliği ise yansıtma güçleridir ve bu değer tamamen yapıldıkları malzemeyle ilgilidir. Türbinlerin hareketli parçası olan kanatlar genellikle mikrodalgalara karşı %30 yansıtma özelliği olan fiberglastan yapılmadır. Bu kanatların eğim ve sapma açıları da radar kesit alanındaki görünümlerini doğrudan etkiler.

Simülasyon sonucu rüzgâr enerji santrallerinin kara radarlarına olan on adet etkisi tespit edilmiştir. Birinci etki, kanatların açılarıdır. Kanatların radar görüş alanına 90 derecede durduğu pozisyonlarda radar etkisi en büyüktür, 0 derecede durduğu pozisyonlarda en düşüktür. Basit hareket eden hedef belirleme metotlarıyla, 0 derecede durduğu pozisyonlar kolaylıkla tespit edilip elenebilir. Ancak 90 derecede durduğu pozisyonlarda kanatların dönüş yönüne doğru, radara yaklaşan ya da radardan uzaklaşan gibi görünen hareketli bir cisim söz konusu olur. Kanatların hızı da hesaba katıldığında klasik metotlar bu durumun tespitinde kullanılamaz, doppler analizi yapmak gerekir. İkinci etki, türbinlerin ve radarın birbirlerine olan mesafesidir. Mesafe azaldıkça etki büyür, mesafe büyüdükçe etki küçülür. Etkinin küçülmesinde perspektif olarak uzaklaştıkça türbinlerin radar görüş alanında daha az yer kaplamasının yanı sıra dünyanın şekli itibariyle görüş alanından tamamen ya da kısmen çıkması da söz konusudur. Üçüncü etki, bir rüzgâr enerji santralindeki türbinlerin birbirlerine olan yakınlıklarıdır. Her türbin birbirinden de yansıtacağı için mikrodalgaları, birbirlerine göre konum ve mesafeleri önemlidir. Türbinler birbirlerine ne kadar yakın olursa radarın her bir türbini ayrı olarak tespit edebilme gücü azalır. Dördüncü etki, asıl görünmek istenen hedefin radarın görüşüne göre türbinlerin arkasında kalma durumudur. Türbin arkasında yarı gölge ve tam gölge olmak üzere iki alan oluşur. Tam gölgede kalan cisimler radara tamamen görünmezdir. Beşinci etki, klasik radar denklemine göre hesaplama yapıldığında gürültü alanı ne kadar büyürse radarın mesafe algısının o kadar yanılacağını gösterir. Altıncı etki, türbinin arkasında kalan yarı gölge bir alanda kalan hedef için tespit edilebilirliğin desibel cinsinden ne kadar azalacağıdır. Yedinci etki, rüzgâr türbinlerinin yüksekliğidir. İhtiyaca göre çok uzun üretilebilen bu tip türbinler uzak mesafelerden de radar görüş alanına girebilirler. Sekizinci etki, kanat açıklıklarının büyüklüğü ve kanatların hızlarıdır. Kanat aralığı büyük ve hızlı dönen türbinler radarda kolaylıkla bir uçak ya da fırtına tipi bir hava muhalefeti olarak zannedilebilir. Dokuzuncu etki, radarlarının alıcı korumalarının belli bir desibele kadar cihazı koruyabiliyor olması ve bu yüzden radarlara çok yakın konumlanmış bir türbinden dönebilecek mikrodalgalarının bu koruyucu sınırı aşarak cihazı çalışmaz hale getirebilmesidir. Onuncu ve son etki en genel olanıdır. Türbinlerin tüm parçalarının ve birden fazla türbinin bir aradayken radar görüş alanını tamamen kaplaması durumunda radar işlevini yitirir.

Tüm bu etkilere karşı iki ana iyileştirme yöntemi vardır: radar açısından, rüzgâr türbinleri açısından. Belli bir alana aynı anda hem radar istasyonu hem rüzgâr enerji santrali kurulması olasılığı düşük olduğundan, radar olan yere santral kurulacaksa rüzgar türbinleri açısından yapılabilecek iyileştirmeler, santral olan bir yere radar istasyonu kurulacaksa radar açısından yapılabilecek iyileştirmeler uygulanabilir. Karşılıklı anlaşmalar sonucu her iki taraflıda iyileştirme yoluna gidilebilir.

Radar açısından yedi tip iyileştirme mevcuttur. Düşük frekanslı uzun mesafe radarları daha geniş bir alan taradıkları için türbinlerin etkisi radar kesit alanında azalabilir. Bir radar istasyonunun kurulum maliyeti bir rüzgâr türbininin kurulum maliyetinden çok daha düşüktür. Bu sebeple rüzgâr enerji santrallerinden etkilenen radarların yerlerinin değiştirilmesi daha verimli ve maliyeti düşük bir çözümdür. Aynı tip bir etkiyi ortadan kaldırabilmek için birden fazla birbirini destekleyen bir radar ağının kurulması da daha düşün maliyetli olacaktır. Bir radarın görmediği alanı farklı bir açıdan bir diğer radar görebilecek ve sonuçta bu ağda bulunan tüm radarların görüntüleri ortak analiz edilerek tam kapsam sağlanabilecektir gözlemlenen alanda. Holografik radar sistemleri de kullanılabilir. Bu tip radarlar tamamen görüntü işleme temellerine dayanır. Konumu bilenen ve sabit bir rüzgâr enerji santralindeki türbinlerinde taşıyıcı mekanizmaları sabit ve konumları bilinen cisimlerdir. Bunlar bir kere analiz edilerek radar hafızasına kaydedilip sonraki taramalarda radar ekranın görünmemeleri sağlanabilir. Bunun yanı sıra bir den fazla tarama sonucu radar hafızasında toplanan bilgi sayesinde her zaman aynı hareketi yapan türbin kanatları da tanımlanarak, hareketi bilindiğinden radar ekranında rüzgâr enerji santrali alanı belirlenebilir. Radar taraflı çözümlerden bir diğeri de radarların yüksek açılara bakmasıdır ancak bu çok verimli olmaz alçak irtifalı hedeflerin görünmemesine sebep olur. Son olarak radarın detay görebilme gücü ne kadar yüksekse birbirine yakın türbinleri o kadar çok birbirinden ayırt edebilir.

Rüzgar enerji santralleri açısından yapılabilecek yedi tip iyileştirme mevcuttur. Malzeme teknolojisindeki gelişmeler çerçevesinde türbinlerin yapımında kullanılan fiberglas malzemenin üzerine hayalet boya sürülerek görünürlüğünü %99, 20 desibele kadar düşürmek mümkün. Ancak bu durumda türbin arkasında kör nokta oluşmasını engellemeyecektir. Telemetre ile bilgi toplama yöntemi ise bir başka çözüm olabilir. Rüzgâr enerji santralinden yakınlarındaki radar tesislerine gerçek zamanlı hız ve pozisyon bilgisi sağlanması türbinin hareketli parçaları için radarların görüntüden türbinleri eleyebilmesini sağlar. Rüzgâr enerji santralleri radar istasyonlarında uzağa kurulabilir. Bu sayede hem radarın görüşünü hiç etkilemez ya da az etkiler. Az etkilediği durumlarda da türbinin arkasında oluşan gölge alanı daha küçük olur. Mesafenin artması sayesinde dünyanın şekli itibariyle türbinlerin radarın tamamen görüş alanından çıkmaları sağlanabilir. Meteorolojik ya da askeri radar istasyonlarının yakınlarına rüzgâr enerji santrallerinin inşa edilme izinleri, kanunlarla güvenlik ve emniyet açısından düzlenebilir. Radar istasyonlarına yakın bir rüzgâr enerji santrali rüzgârın o konumda verimli olmasından ötürü kurulmak zorunda kalındığında, santral içerisine çevredeki istasyonlara bilgi sağlayacak bir yardımcı radar inşa edilebilir. Bu gibi durumlarda türbinlerin santral içerisindeki konumlarının radarın görüş alanına göre lineer olması sağlanarak, radar tarafından bakıldığında sanki sadece bir adet türbin görünüyormuş gibi olması sağlanabilir.

Sonuç olarak, rüzgâr enerji santrallerinin kara radarlarına etkisi vardır. Kısa vadeli çözümler problemin farkındalığını arttırmak, yetkili ulusal kurumlarla iş birliği içerisinde olmak ve sinyal işleme araştırmalarını desteklemektir. Radar araştırma bütçelerine ulusal ve uluslararası arenada verilecek desteklerle; modelleme yazılımlarının ve sinyal işleme teknolojilerinin geliştirilmesi, rüzgâr enerji santralinin etki alanına giren yerlerde daha çok ve daha yüksek radar istasyonlarının inşa edilebilmesi sağlanabilir. Rüzgâr enerji santrallerinin yerlerini değiştirmek tercih edilecek bir çözüm değildir. Rüzgâr enerji santrallerinin araştırma geliştirme bütçelerin daha çok radar dostu türbinlerin inşa edilebilmesi için malzeme araştırmalarına ayırılabilir. Bir türbinin kanatlarının radar görünmez olabilmesi için özel boyayla boyanması standart maliyetin üzerine %10 - %20 artış getirir. Bu şartlar altında uygulanabilecek en iyi yöntemler yaşlanmış radar istasyonlarının yerlerini değiştirmek ya da istasyonları yeni teknoloji donanımlarla donatmak olacaktır. Bu noktada yetkililer tarafından radikal kararlar alınması gerekmektedir bir alandaki türbinlerin etkileri lineer olarak toplanabileceği gibi bazen çok rastgele ve kaotik olabilir. Bu gibi durumlar için çoklu etkilerin araştırılması faydalı olacaktır. Rüzgâr enerji santrallerinin mobil radar istasyonlarına olan etkileri de tamamen ayrı bir araştırma konusudur. Denizlere kurulan rüzgâr enerji santrallerinin gemi, kara ya da uçak radarları tarafından tespiti daha basittir çünkü arka plan tek tiptir, etrafta çok fazla gürültü kaynağı yoktur. Etkinin azaltılabilmesi için silindir yerine konik türbin gövdeleri kullanılabilir. Yüzey alanı küçüldükçe radara etkisi azalır. Bu tip bir tasarımın mukavemetinin de incelenmesi gerekmektedir.

1. INTRODUCTION

Most actual surfaces and manufactured environments such as wind power plants produces irregular reflections and scattered fields, added to or replacing the simple specular reflection. This causes random errors in both azimuth and elevation measurements, and extends the spread of range and Doppler error. The effects of local features were noted in low-frequency navigation systems and in radar during the 1950's and 1960's (Barrios, 1994). Wind power in Turkey is gradually expanding in capacity. Many wind farm projects are delayed or denied pending long-term assessments of radar impact.The most effected types of radars are defense, weather and air traffic control radars. There are methods for modeling the impact of wind turbines on radar returns. It is important to simulate the magnitude and Doppler shift that would occur in order to take corrective actions. Not only the growth of the number of wind power plants, but also the increasing size of wind power plants and the use of taller turbines, which can impact radars from a greater distance, are the factors increasing the interference. Since the blades are moving, the echoes will have a velocity and can be mistaken for real weather. Since weather is always in motion and most clutter targets such as buildings are stationary, the basic clutter removal schemes filter targets that essentially have no or very little motion. Radar clutter is defined as unwanted echoes, typically from the ground. The designer of a Doppler radar is generally interested in discriminating against these unwanted returns; hence, the properties of those unwanted echoes must be understood to provide an effective radar design. Visibility of a target increases on radar display when its RCS increases. RCS changes according to the shape of the target and its movement with respect to the target. The performance of radar describes how far it can see (range), how accurately it can measure the position of an object (accuracy), how well it can resolve objects near each other (resolution) and how well it can see objects against a background (clutter improvement). Radar issues have stalled so many projects all around the world for a while until the impact was realized and understanding of the impact with solutions emerged.

2. PULSED DOPPLER RADARS

The Doppler effect is the change in the frequency of a wave received by an observer, compared to the frequency with which it was emitted. The effect takes place whenever there is motion between the emitter and receiver.

We can explain the Doppler effect in diagrams as follows: the source move towards observer B and away from observer A. The wavecrests are pilling in front of the source and thus the crests reach B at time intervals which are shorter than those on emission. Thus the received period is smaller and hence the frequency is larger. On the other hand, the crests reach A at longer time intervals and thus the measured frequncy is smaller, Figure.

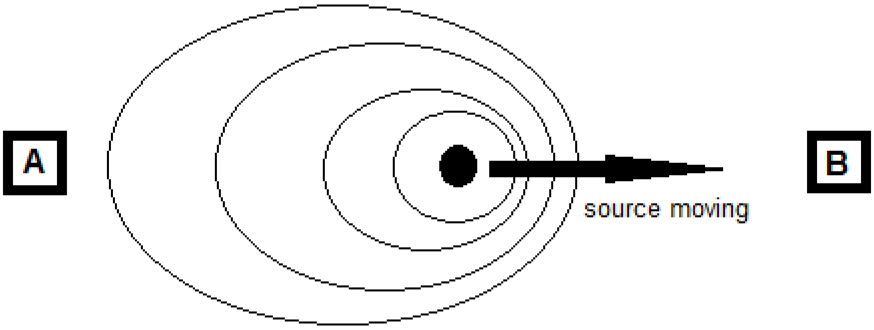


Figure 2.1 : A is approaching B and moves away from A

We can analyze this phenomenon in detail in the following way. Consider first the case when the observer is at rest and the emitter moves towards him. Suppose that at time t=0 the emitter emits a wave crest which reaches the receiver at a time of t seconds later. The second crest is emitted by the emitter at time T_0 where T_0 is the period of the wave, i.e. the emitted frequency if $f_0=1/T_0$. At what time does the receiver receive this second crest? Notice that during this interval of time T_0, the emitter has moved towards the receiver. The speed of the source is v_s and the wave speed is c. The wavecrest has therefore a shorter distance to travel.

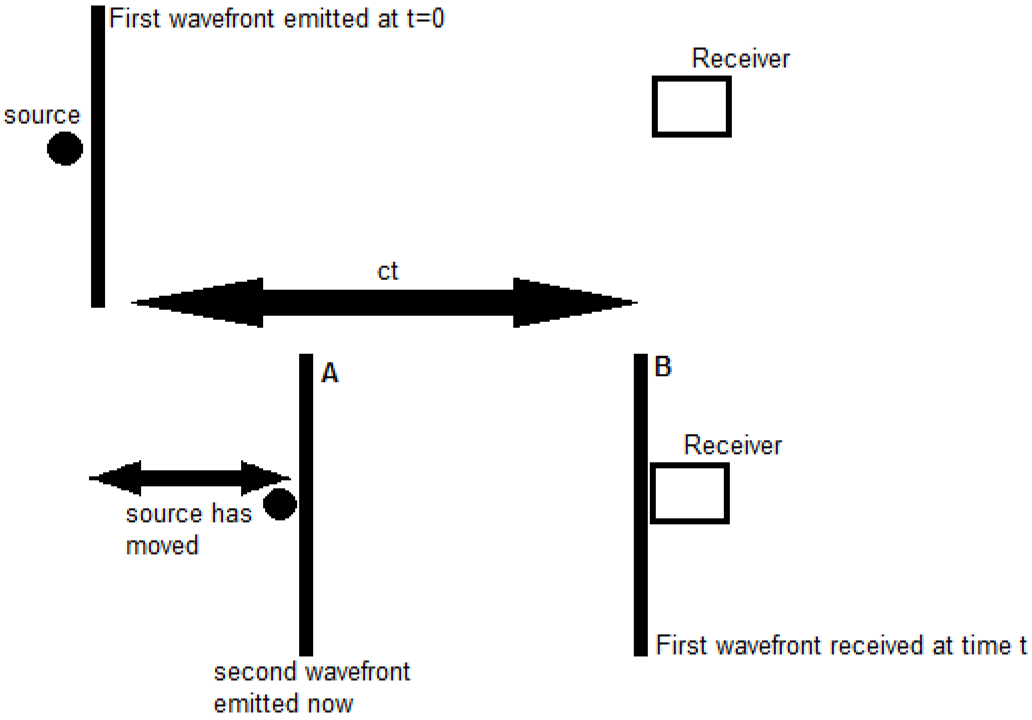


Figure 2.2 : The first wavefront is emitted at t=0 and is received a time of t seconds later

The second wavefront is emitted T seconds after the first. It will be received by the observer at a time less than T since the source is closer to the observer when it emits the second wavefront.

The time taken for the second wavecrest to travel the distance AB in the figure is $\frac{ct-V_sT_0}{c} = t - \frac{v_s}{c}T_0$ and thus the time of arrival is $T_0 + t - T_0\frac{V_s}{c} = t + T_0\left(1 - \frac{v_s}{c}\right)$. That ,s to say, the second wavefront arrives a time of $T_0\left(1 - \frac{v_s}{c}\right)$ after the first one. Hence the period of this wave as far as the observer is concerned is $T = T_0\left(1 - \frac{v_s}{c}\right)$. Thus the frequency measured by the receiver is, $f = \frac{1}{T}$

$$f = f_0\frac{1}{1 - \frac{v_s}{c}} = f_0\frac{c}{c - v_s}$$

This shows as the emitter approaches the receiver the receiver measures a higher freqeuncy than what was sent out. If the emitter is receding from the observer the same formula applies but the velocity of the source must be taken as negative.

Consider now the case of a stationary emitter and a receiver moving with velocity v_r. We can get the answer from the previous formula by the use of the concept of relative velocity. The receiver is free to call himself at rest in which case the receiver is coming at him with velocity v_r. In addition, the wave appears to be moving with velocity c + v_r. Hence, the previous formula gives the following answer for the frequency received by the receiver:

$$f = f_0 \frac{(c + v_r)}{(c + v_r) - v_r} = f_0 \frac{c + v_r}{c} \qquad \textbf{(2.1)}$$

Again if the receiver moves towards the emitter the velocity is taken as a positive number and negative otherwise (Sander and others, 2006).

$$v_r = v_s \cos\theta$$

where v_s is the velocity of the object (source of waves) with respect to the medium, and θ is the angle between the source’s forward velocity and the line of sight from the source to the observer.

A Doppler radar is defined by the IEEE standard radar definitions as one that uses the Doppler Effect to determine the radial component of radar target velocity or to select targets having particular radial velocities. When a Doppler radar uses pulse transmissions it is called PD radar.

A general objective in Doppler radar processor design is to maintain a linear response over the full dynamic range of the clutter and design the processor with an improvement factor sufficient to reduce the clutter residue to the receiver noise level. The residues of large clutter echoes exist because their amplitude is greater than the improvement factor, see Figure 2.1.

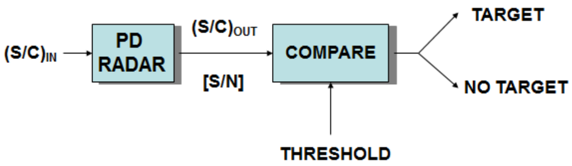


Figure 2.3 : Improvement factor flow diagram[1].

$$I_f = \left(\frac{S}{C}\right)_{out} \left(\frac{C}{S}\right)_{in} = \left(\frac{C_{in}}{C_{out}}\right) G_{av} \qquad \textbf{(2.2)}$$

where:

---

[1] S/N is the ratio, e.g. -30 dB means the signal strength is 1/1000 of the strength of the noise

C_{in} is the strength of clutter at clutter input

C_{out} is the strength of the clutter at clutter output

G_{av} is the average filter gain for moving targets

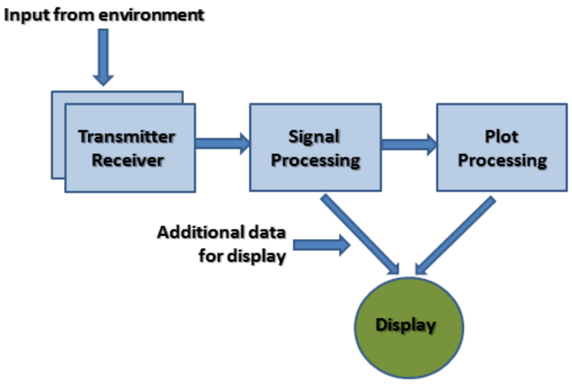


Figure 2.4 : Simple illustration of what happens inside radar equipment.

Radar can be calibrated to neglect stationary objects within its LOS. Signal processing is for identifying moving targets and plot processing is for stationary ones. What computers do is analysing the strength of the returned pulse, time it took to travel to the object and back, and Doppler shift of the pulse, see Figure 2.2. Velocity and reflectivity are two main types of radar reading data. The strength of the energy, which is returned to the radar after it bounces off targets, forms the reflectivity data. The Doppler shift of the returned energy forms the velocity data (Cheney and Borden, 2009). The change in frequency is called the Doppler frequency and it is approximately (Gipe, 2009):

$$f_d \cong \frac{(2 f_t v_r)}{c} \tag{2.2}$$

where:

f_d is the frequency difference between the transmitted and returned signals

f_t is the frequency of the transmitted signal

v_r is the velocity of the target toward the transmitter

c is the speed of light (~300000 km/s)

e.g. if the transmitted frequency is 10000 MHz and the velocity of the target toward the transmitter is 60 km/h, the Doppler frequency is:

$$f_d \cong \frac{\left(2 \times 10000 \times \frac{1}{60}\right)}{300000} \cong 0.001\,MHz$$

Thus, the frequency of the returned signal is 0.001 MHz different from the transmitted frequency. If the target was approaching the transmitter; the Doppler would be added, in otherwise it would be subtracted, see Figure 2.3.

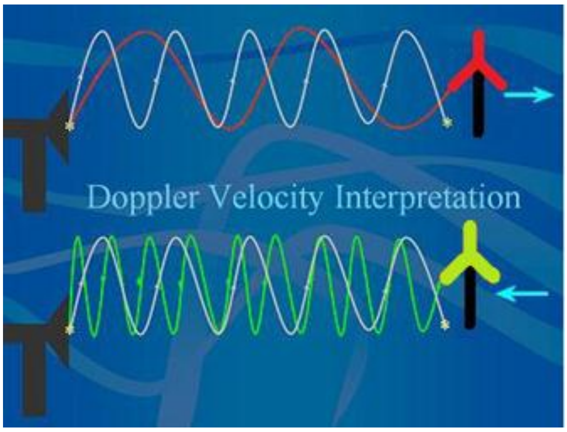


Figure 2.5 : Doppler velocity interpretation.

The returned microwaves change their wavelength when they hit a moving object away or toward the radar. Red colour points a target moving away from the radar and green colour points a target moving toward the radar in distinguishing velocity data, see Figure 2.4.

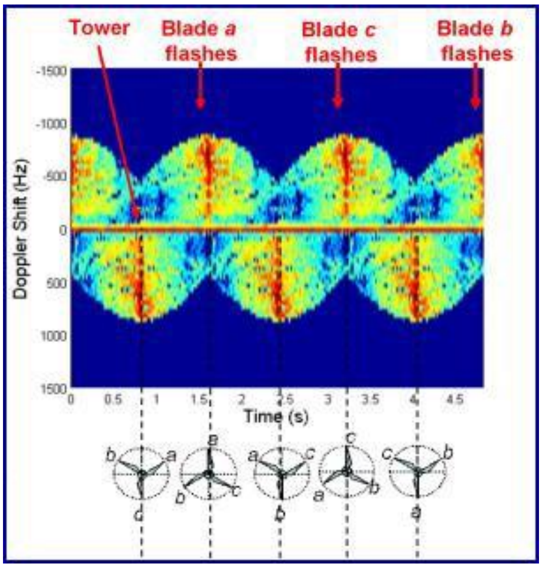


Figure 2.6 : Rotation of blades leads to Doppler shift varying sinusoidally (Brenner, 2008).

Radial velocity is essential for pulse-Doppler radar operation. As the reflector moves between each transmit pulse, the returned signal has a phase difference or *phase shift* from pulse to pulse. This causes the reflector to produce Doppler modulation on the reflected signal.

Pulse-Doppler radar uses the following signal processing criteria to exclude unwanted signals from slow-moving objects. This is also known as clutter rejection. Rejection velocity is usually set just above the prevailing wind speed (15 to 150 km/hour).

$$\left|\left(\frac{Doppler\ Frequency \times C}{2 \times Transmit\ Frequency}\right)\right| > Velocity\ Threshold$$

3. WIND POWER PLANTS

A wind power plant is an area including more than one wind turbine to generate electric (Stewart, 2004). Wind power plants have both point clutter and a Doppler component. Most of the energy is scattered from the stationary parts of the turbine and its supporting structure, see Figure 3.1. RCS of corner reflectors, flat plates, single curved surfaces, doubly curved surfaces, straight edges and curved edges can all be calculated separately (Wheeler, 1967). The overall result would be the amount of point clutter.

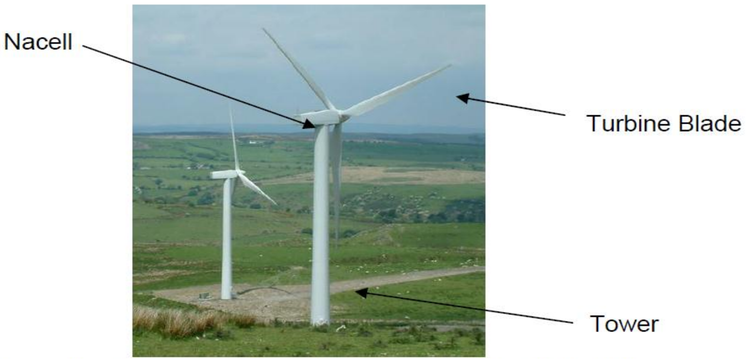


Figure 3.1 : Main parts of a standard wind turbine.

Another property of wind turbines is their reflectivity; what they are made of. Most of the turbine blades are made of glass reinforced plastic that is 30% reflective to microwaves. Other factors such as the pitch and yaw angles of the turbine and the individual pitch of the blades may also affect the RCS. In Figure3.2, wavelength of the backscattered signal changes with time according to thr position of the turbine blades

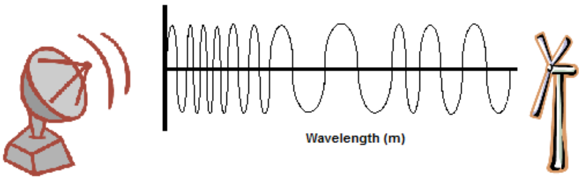


Figure 3.2 : Wavelength changing in time.

RCS (Appendix A.1) of a wind turbine can be calculated with the below equation[2]:

$$\sigma = \lim_{r\to\infty}\left[4\pi r^2 \frac{|E_s|^2}{|E_i|^2}\right] \tag{3.1}$$

where:

E_s is the power density that is stopped by the target

E_i is the power density in the range r

r is radius of the sphere, where RCS propagate in a spherical form.

Table 3.1 : Values for RCS calculation

	Generic Wind Turbine	Vestas V90-1.8MV
Tower height	50 m	80 m
Tower RCS	80 m^2	?
Blade length	30 m	45 m
Blade RCS	9 m^2	?

Scaling factors are derived for the tower and blades separately:

$$A_T = \frac{H_V}{H_G} = \frac{80\ m}{50\ m} = 1.6$$

$$A_B = \frac{L_V}{L_G} = \frac{45\ m}{30\ m} = 1.5$$

where

A_T is the tower height scaling factor

H_V is the height of the Vestas turbine

H_G is the height og the generic turbine

A_B is the blade length scaling factor

---

[2] symbol: σ and unit: dB or m^2
where $10\log_{10} RCS\ (m^2) = RCS\ (dB)$

L_V is the length of the blades of the Vestas turbine

L_G is the length of the blades of the generic turbine

The generic wind turbine RCS values given inthe report are then multiplied by these scaling factors to arrive at nominal RCS values for the Vestas V90-1.8MV turbine:

$$RCS_{TV} = RCS_{TG} \times A_T = 80\ m^2 \times 1.6 = 128\ m^2$$

$$RCS_{BV} = RCS_{BG} \times A_B = 9\ m^2 \times 1.5 = 13.5\ m^2$$

where

RCS_{TV} is the RCS of the tower of the Vestas turbine

RCS_{TG} is the RCS of the tower of the generic turbine

RCS_{BV} is the RCS of the blades of the Vestas turbine

RCS_{BG} is the RCS of the blades of the generic turbine

Summing the RCS_{TV} and RCS_{BV} values together, we arrive at a total RCS of 141.5 m^2. When converted to dBsm, the value is:

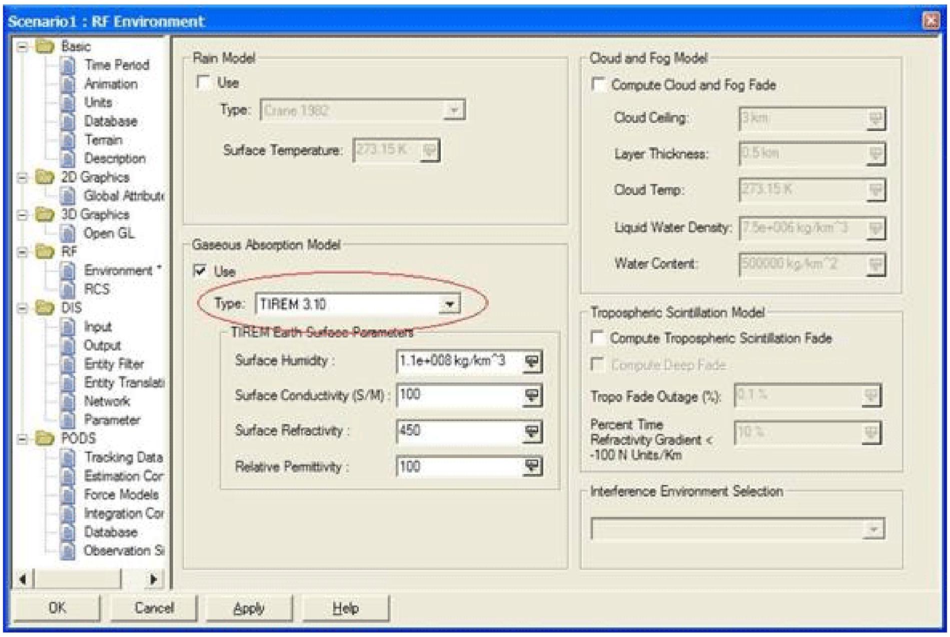
$$RCS_V = 10\log(141.5) = 21.51\ dBsm$$

4. SIMULATION

4.1 Verification and Validation of AGI Technology

STK is a physics-based software package from AGI. The core of STK is a geometry engine that is designed to determine the time-dynamic position and attitude of assets, determining dynamic spatial relationships among all of the objects under consideration including the quality of those relationships or accesses given a number of complex, simultaneous constraining conditions.

STK combines with TIREM to provide the functionality needed to calculate RF propagation loss over irregular terrain from 1MHz to 20 GHz.



Rain Model
☐ Use
Type: Crane 1982
Surface Temperature: 273.15 K

Gaseous Absorption Model
☑ Use
Type: TIREM 3.10
TIREM Earth Surface Parameters
Surface Humidity : 1.1e+008 kg/km^3
Surface Conductivity (S/M) : 100
Surface Refractivity : 450
Relative Permittivity : 100

Cloud and Fog Model
☐ Compute Cloud and Fog Fade
Cloud Ceiling: 3 km
Layer Thickness: 0.5 km
Cloud Temp: 273.15 K
Liquid Water Density: 7.5e+006 kg/km^3
Water Content: 500000 kg/km^2

Tropospheric Scintillation Model
☐ Compute Tropospheric Scintillation Fade
☐ Compute Deep Fade
Tropo Fade Outage (%): 0.1 %
Percent Time Refractivity Gradient < -100 N Units/Km: 10 %

Interference Environment Selection

Figure 4.1 TIREM

AGI Components is a family of class libraries that leverage the STK desktop product by using its algorithms and file formats and building off its analysis. The libraries are verified and validated against STK as the benchmark. AGI expects Components to achieve the same numerical accuracy as STK, and a large part of the test suite is dedicated to ensuring that. More than 3,000 individual tests are run on every build of components using NUnit as the framework. NCover informs the test group of any code that goes untested. If a feature cannot be tested with STK, other methods are used. For instance, AGI does limited testing against other data sources such as the sAstronomical Almanac. Engineers also test for specific well-defined results and for edge cases (correct error handling, pathological cases, etc.) All told, AGI's code coverage is more than 90% with the remaining 10% tending to be error handling. All AGI tests have built-in acceptance criteria on a pass-fail basis: AGI does not ship unless all tests pass (AGI, 2009).

4.2 Primary Decisions for Simulation

Wind turbine model used in this paper is a horizontal axis type and has standard three blades. The radar type mentioned throughout this paper is monostatic (which means both the receiver and the transmitter are at the same place, not at different locations), on a stationary platform and has coherent detectors (which compares the echo signals with a phase reference in order to be able to use the Doppler frequency information later). AGI STK9 is used to design the main simulation. Separate calculations on radar systems are driven with MATLAB.

Each turbine rotates at a steady rate in the simulation, but the rates of each of them are different and blade rotation is started from a random angular position. It would be unrealistic if all the turbines start to rotate from the same position with same blade speeds.

In this scenario, real facts are taken into account: The proposed Riviera Wind Farm near Riviera, Texas, is to be composed of 75 Vestas V90-1.8MW wind turbines. The wind farm is to be located between 9 and 11.5 nautical miles from the Raytheon DASR-11 primary surveillance radar in use by NAS Kingsville. Due to the proximity of the turbines and the radar, significant interference effects are possible that may inhibit safe air space operation.

4.3 Simulation Walkthrough

See from Figure 4.1 through 4.16 for the whole setup, scenario and snaphots of simulation while running.

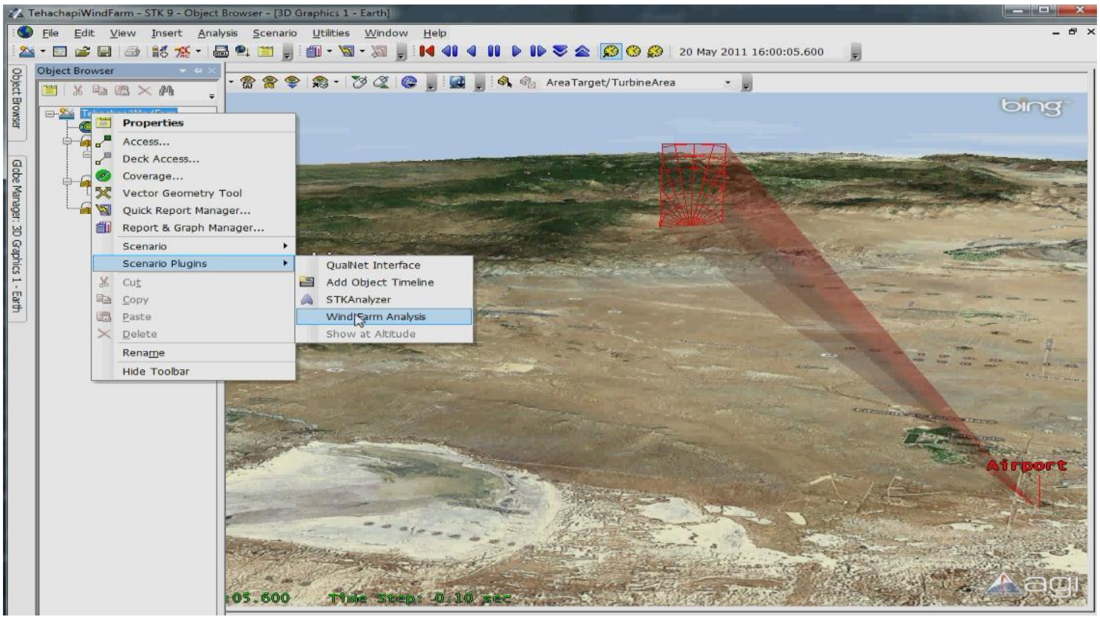


Figure 4.2 Main simulation screen of and how to run Wind Farm analysis.

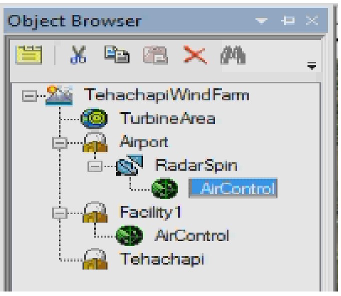
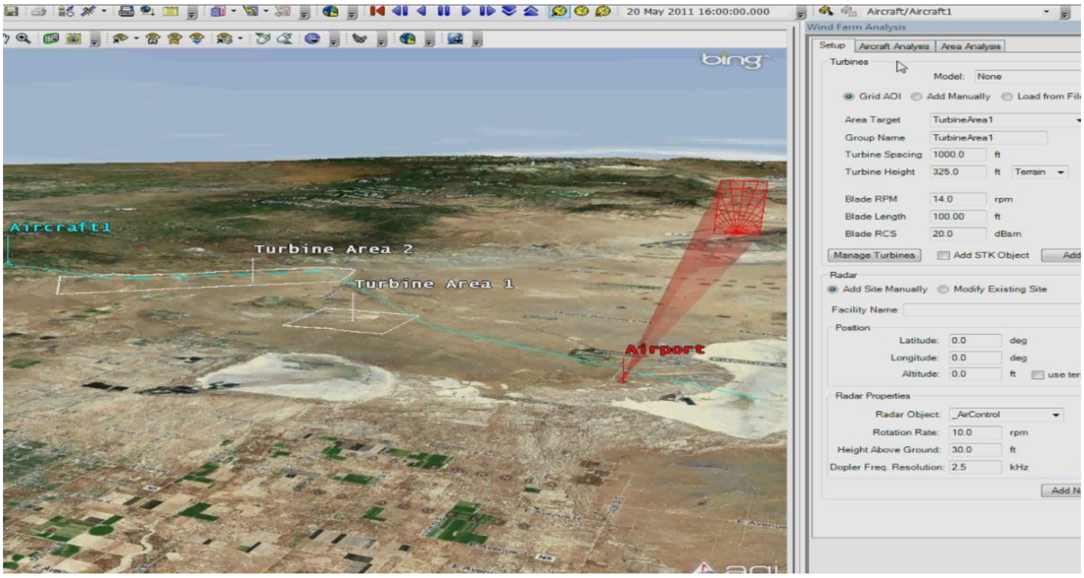


Figure 4.3 Main project subtrees.

Jamming analysis can be accomplished with the Radar module. The Radar module enables us to identify jammers (monostatic radars and source transmitters) and assess their impact on the performance of our radar system. In this simulation, we are going to factor in the effect of jamming on Search/Track radar.



Turbines

Model: None

● Grid AOI ○ Add Manually ○ Load from Fil

Area Target: TurbineArea1
Group Name: TurbineArea1
Turbine Spacing: 1000.0 ft
Turbine Height: 325.0 ft Terrain
Blade RPM: 14.0 rpm
Blade Length: 100.00 ft
Blade RCS: 20.0 dBsm

☐ Add STK Object

Radar

● Add Site Manually ○ Modify Existing Site

Facility Name:

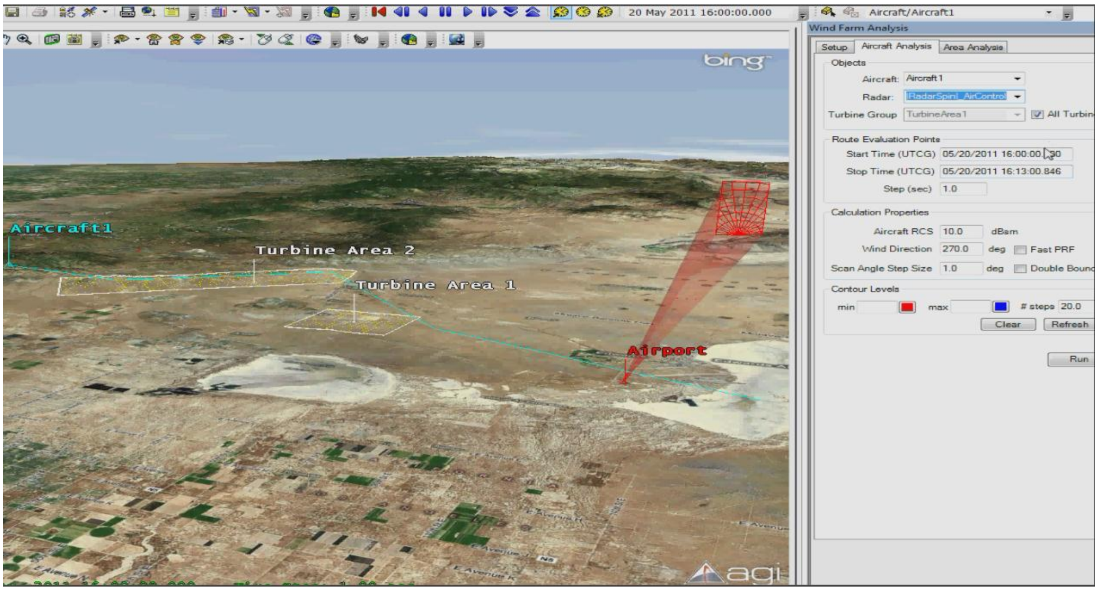
Position

Latitude: 0.0 deg
Longitude: 0.0 deg
Altitude: 0.0 ft ☐ use ter

Radar Properties

Radar Object: _AirControl
Rotation Rate: 10.0 rpm
Height Above Ground: 30.0 ft
Dopler Freq. Resolution: 2.5 kHz

Figure 4.4 Scenario setup.



Objects

Aircraft: Aircraft1
Radar: RadarSpin1_AirControl
Turbine Group: TurbineArea1 ☑ All Turbin

Route Evaluation Points

Start Time (UTCG): 05/20/2011 16:00:00.30
Stop Time (UTCG): 05/20/2011 16:13:00.846
Step (sec): 1.0

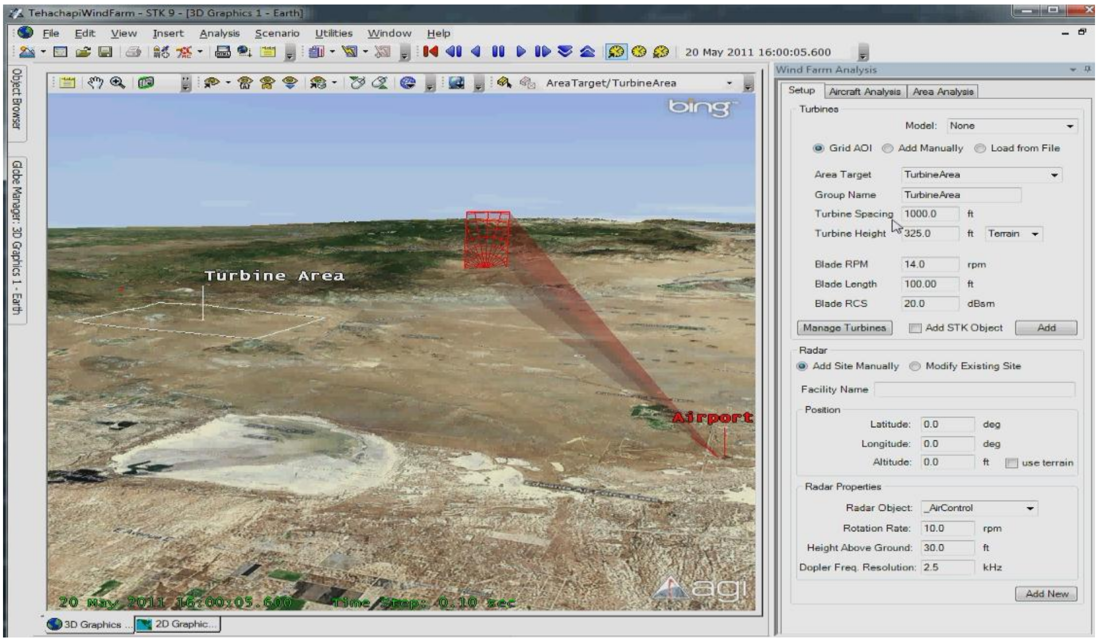
Calculation Properties

Aircraft RCS: 10.0 dBsm
Wind Direction: 270.0 deg ☐ Fast PRF
Scan Angle Step Size: 1.0 deg ☐ Double Bounc

Contour Levels

min 🟥 max 🟦 # steps 20.0

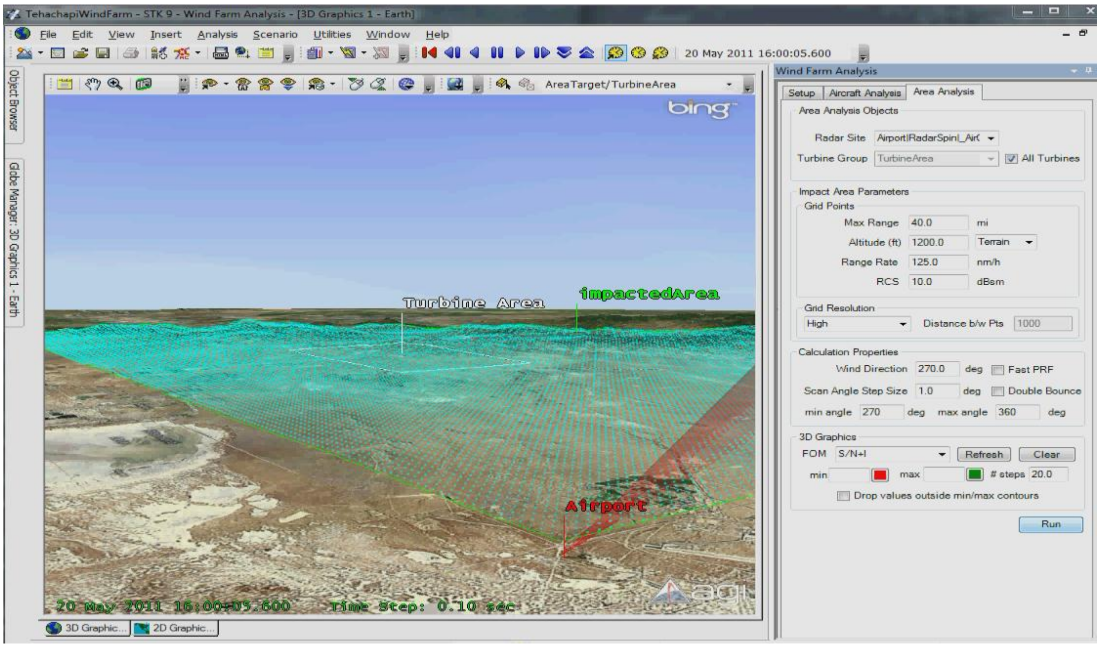
Figure 4.5 Aircraft analysis setup.



Turbines
Model: None
● Grid AOI ○ Add Manually ○ Load from File
Area Target: TurbineArea
Group Name: TurbineArea
Turbine Spacing: 1000.0 ft
Turbine Height: 325.0 ft Terrain
Blade RPM: 14.0 rpm
Blade Length: 100.00 ft
Blade RCS: 20.0 dBsm
☐ Add STK Object

Radar
● Add Site Manually ○ Modify Existing Site
Facility Name:
Position
Latitude: 0.0 deg
Longitude: 0.0 deg
Altitude: 0.0 ft ☐ use terrain
Radar Properties
Radar Object: _AirControl
Rotation Rate: 10.0 rpm
Height Above Ground: 30.0 ft
Dopler Freq. Resolution: 2.5 kHz

Figure 4.6 Wind farm analysis setup.



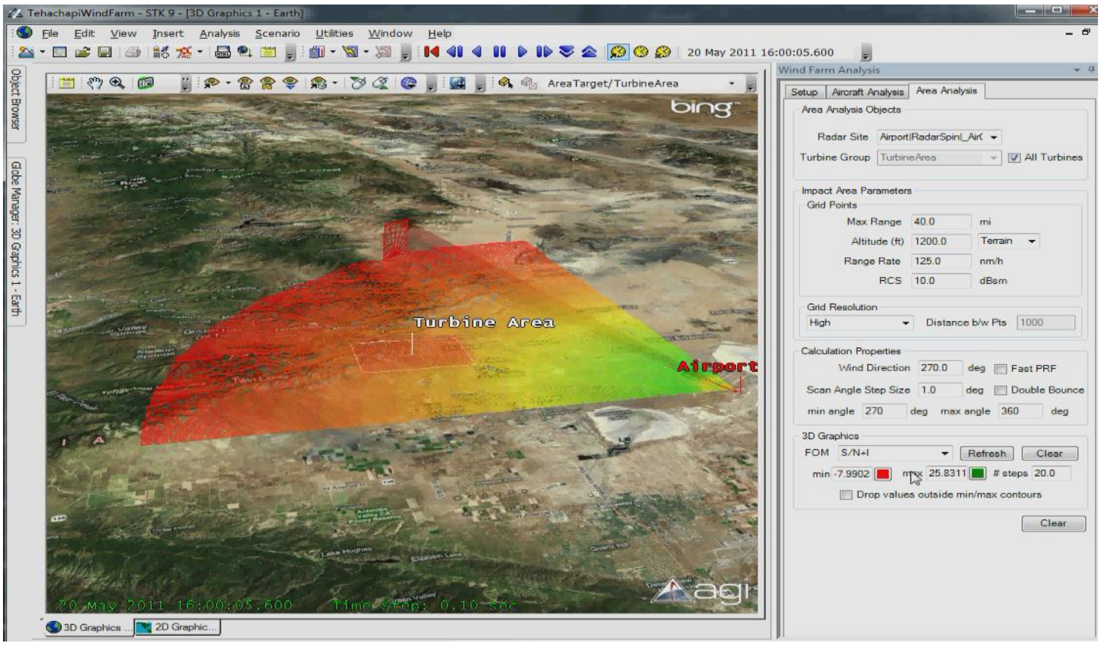
Area Analysis Objects
Radar Site: Airport/RadarSpin/_AirC
Turbine Group: TurbineArea ☑ All Turbines

Impact Area Parameters
Grid Points
Max Range: 40.0 mi
Altitude (ft): 1200.0 Terrain
Range Rate: 125.0 nm/h
RCS: 10.0 dBsm
Grid Resolution
High Distance b/w Pts 1000

Calculation Properties
Wind Direction: 270.0 deg ☐ Fast PRF
Scan Angle Step Size: 1.0 deg ☐ Double Bounce
min angle 270 deg max angle 360 deg

3D Graphics
FOM: S/N+I
min 🟥 max 🟩 # steps 20.0
☐ Drop values outside min/max contours

Figure 4.7 Area Analysis setup.



Area Analysis Objects

Radar Site: AirportRadarSpin|_AirC

Turbine Group: TurbineArea ☑ All Turbines

Impact Area Parameters

Grid Points

Max Range: 40.0 mi

Altitude (ft): 1200.0 Terrain

Range Rate: 125.0 nm/h

RCS: 10.0 dBsm

Grid Resolution: High Distance b/w Pts 1000

Calculation Properties

Wind Direction: 270.0 deg ☐ Fast PRF

Scan Angle Step Size: 1.0 deg ☐ Double Bounce

min angle 270 deg max angle 360 deg

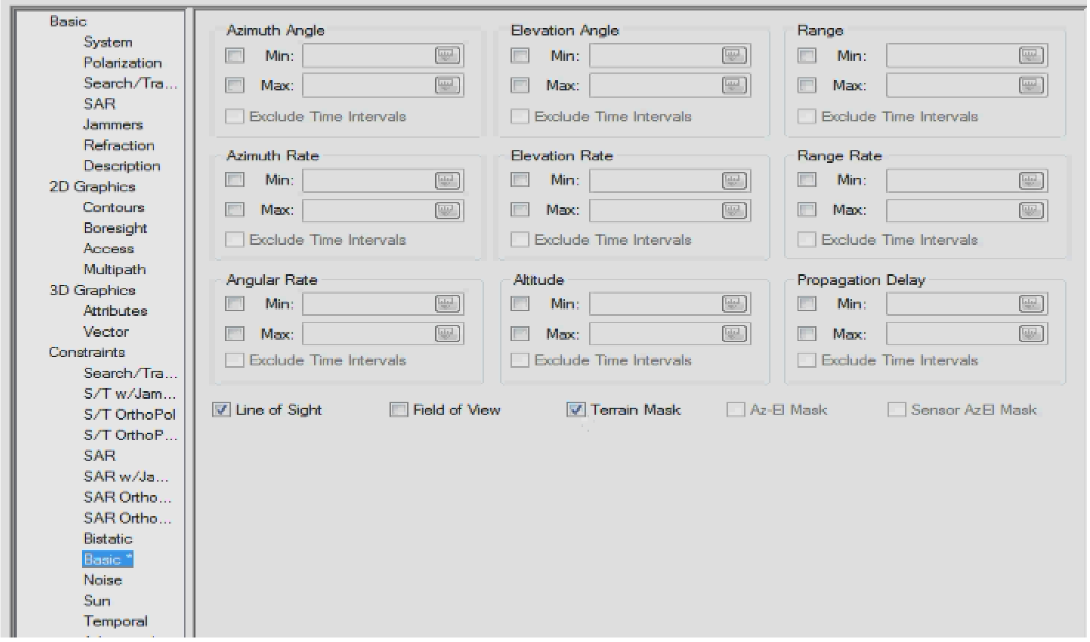
3D Graphics

FOM: S/N+I

min -7.9902 🟥 max 25.8311 🟩 # steps 20.0

☐ Drop values outside min/max contours

Figure 4.8 Area coverage of radar without terrain masking.



Azimuth Angle: ☐ Min: ☐ Max: ☐ Exclude Time Intervals

Elevation Angle: ☐ Min: ☐ Max: ☐ Exclude Time Intervals

Range: ☐ Min: ☐ Max: ☐ Exclude Time Intervals

Azimuth Rate: ☐ Min: ☐ Max: ☐ Exclude Time Intervals

Elevation Rate: ☐ Min: ☐ Max: ☐ Exclude Time Intervals

Range Rate: ☐ Min: ☐ Max: ☐ Exclude Time Intervals

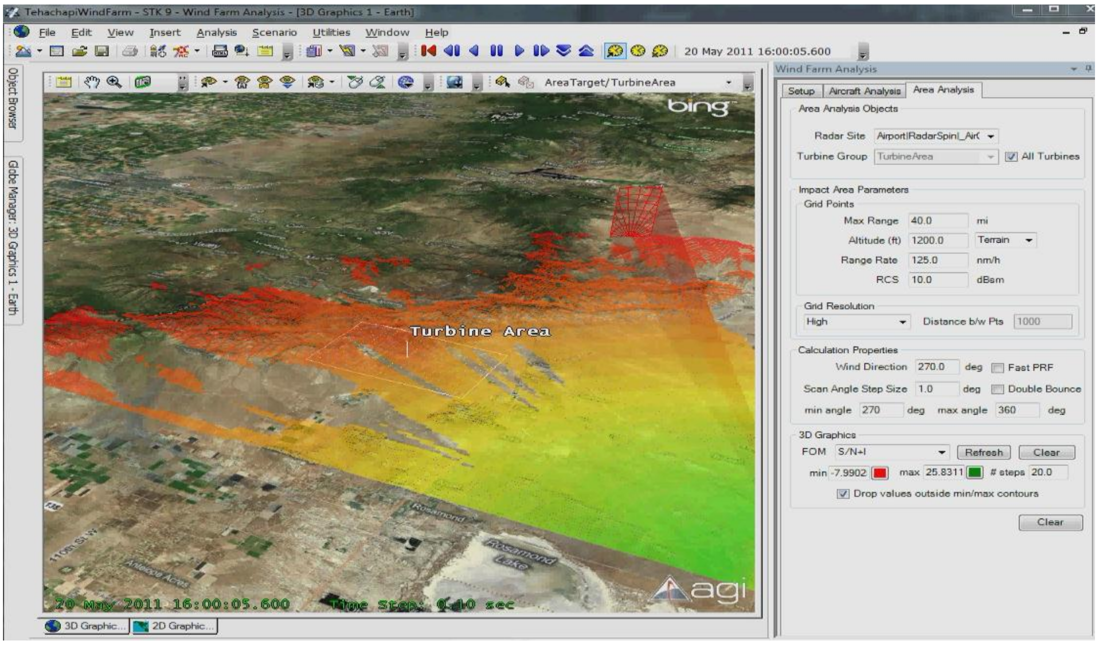
Angular Rate: ☐ Min: ☐ Max: ☐ Exclude Time Intervals

Altitude: ☐ Min: ☐ Max: ☐ Exclude Time Intervals

Propagation Delay: ☐ Min: ☐ Max: ☐ Exclude Time Intervals

☑ Line of Sight ☐ Field of View ☑ Terrain Mask ☐ Az-El Mask ☐ Sensor AzEl Mask

Figure 4.9 Applying terrain masking.



Area Analysis Objects

Radar Site: Airport|RadarSpin|_AirC
Turbine Group: TurbineArea ☑ All Turbines

Impact Area Parameters

Grid Points

Max Range: 40.0 mi
Altitude (ft): 1200.0 Terrain
Range Rate: 125.0 nm/h
RCS: 10.0 dBsm

Grid Resolution: High
Distance b/w Pts: 1000

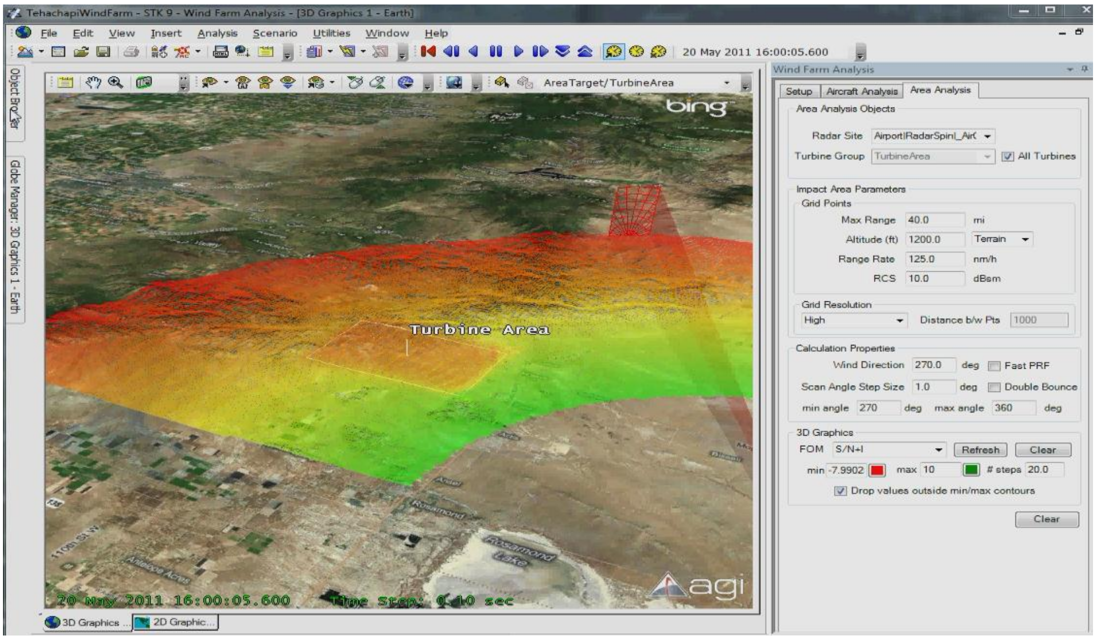
Calculation Properties

Wind Direction: 270.0 deg ☐ Fast PRF
Scan Angle Step Size: 1.0 deg ☐ Double Bounce
min angle: 270 deg max angle: 360 deg

3D Graphics

FOM: S/N+I
min: -7.9902 🟥 max: 25.8311 🟩 # steps: 20.0
☑ Drop values outside min/max contours

Figure 4.10 Area coverage of radar with terrain masking applied.



Area Analysis Objects

Radar Site: Airport|RadarSpin|_AirC
Turbine Group: TurbineArea ☑ All Turbines

Impact Area Parameters

Grid Points

Max Range: 40.0 mi
Altitude (ft): 1200.0 Terrain
Range Rate: 125.0 nm/h
RCS: 10.0 dBsm

Grid Resolution: High
Distance b/w Pts: 1000

Calculation Properties

Wind Direction: 270.0 deg ☐ Fast PRF
Scan Angle Step Size: 1.0 deg ☐ Double Bounce
min angle: 270 deg max angle: 360 deg

3D Graphics

FOM: S/N+I
min: -7.9902 🟥 max: 10 🟩 # steps: 20.0
☑ Drop values outside min/max contours

Figure 4.11 Maximum contour value set to 10.

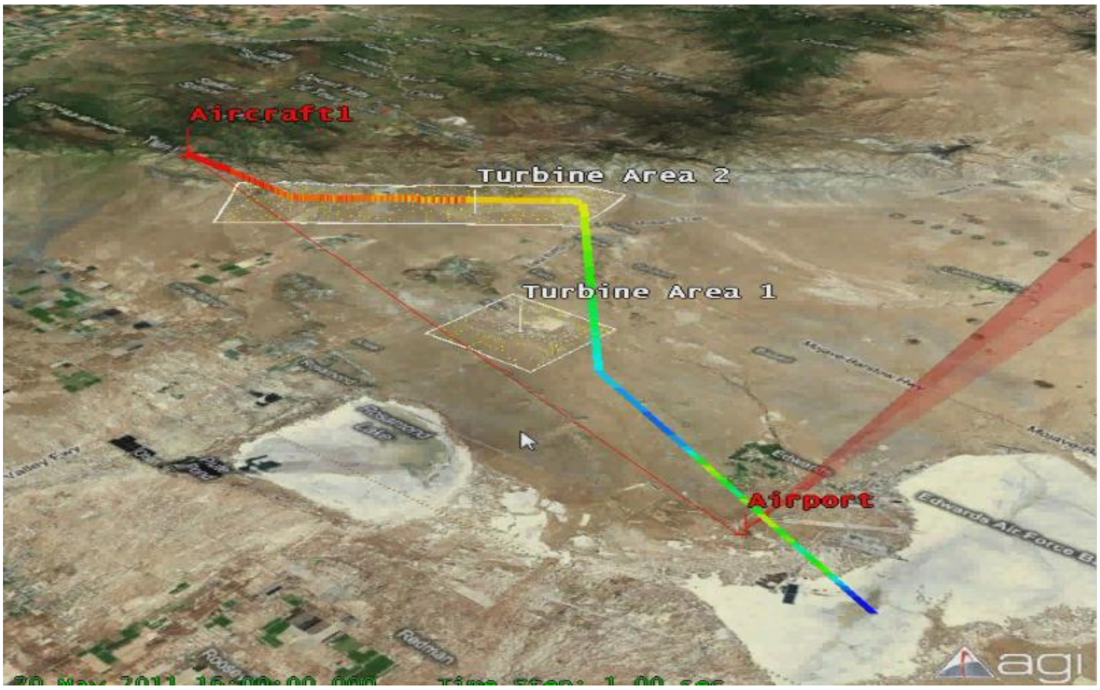


Figure 4.12 Running simulation.

The following four figures shows the Doppler analysis.

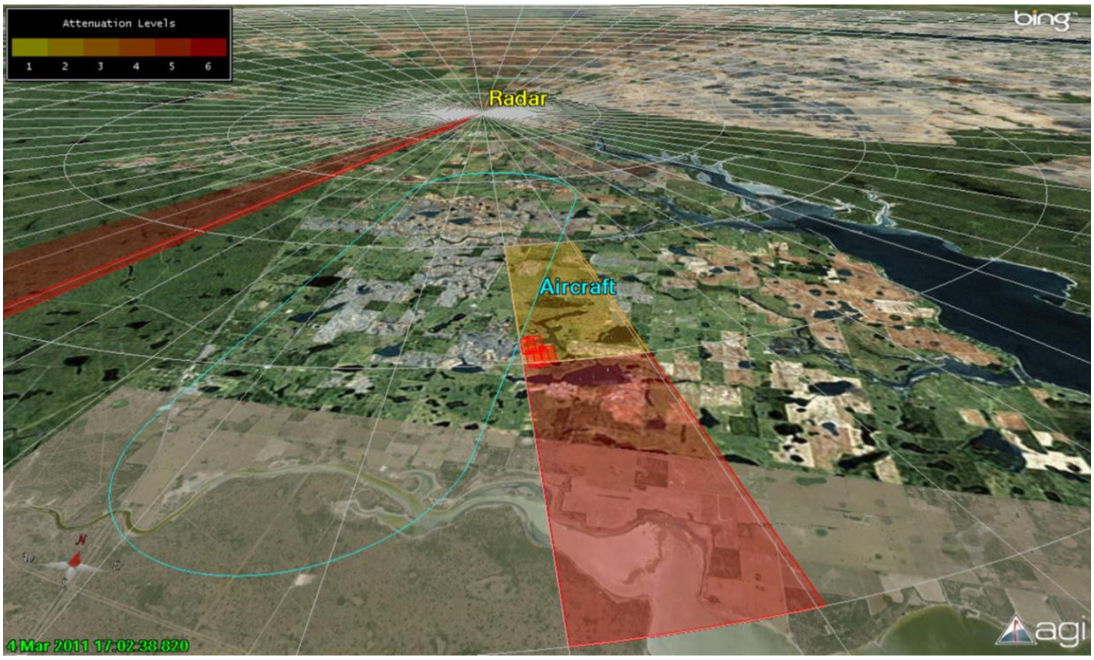


Figure 4.13 Second Pass: Phase 1 Plug-In.

Figure 4.14 Second Pass: Phase 1 Plug-In Doppler Cells and clutter.

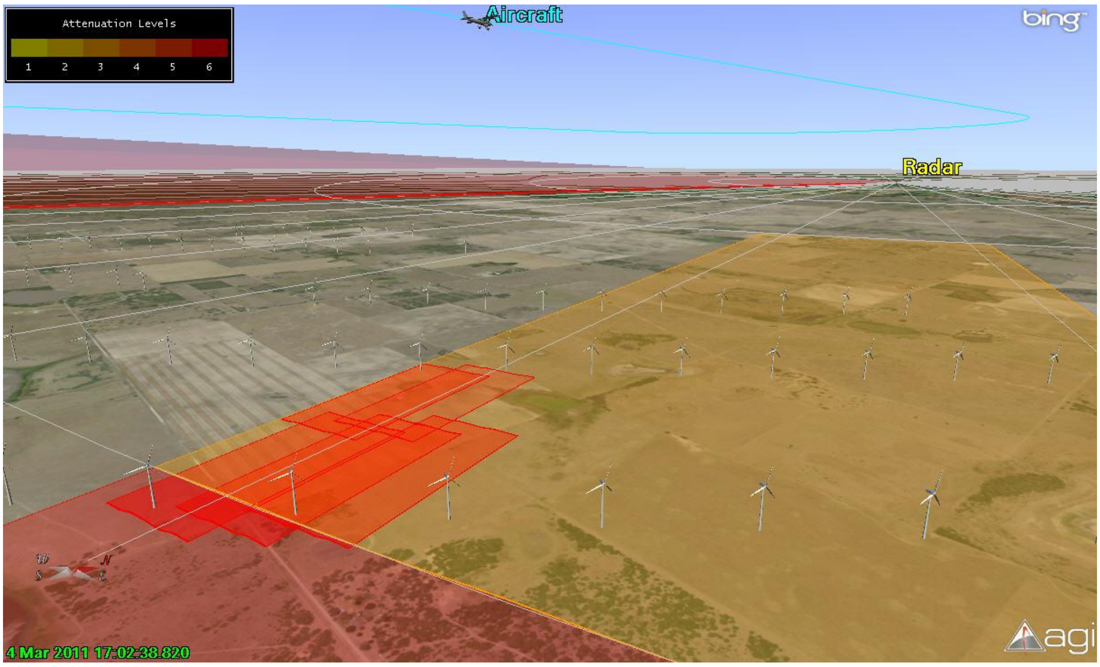


Figure 4.15 Second Pass: Phase 1 Plug-In Doppler cells and clutter.

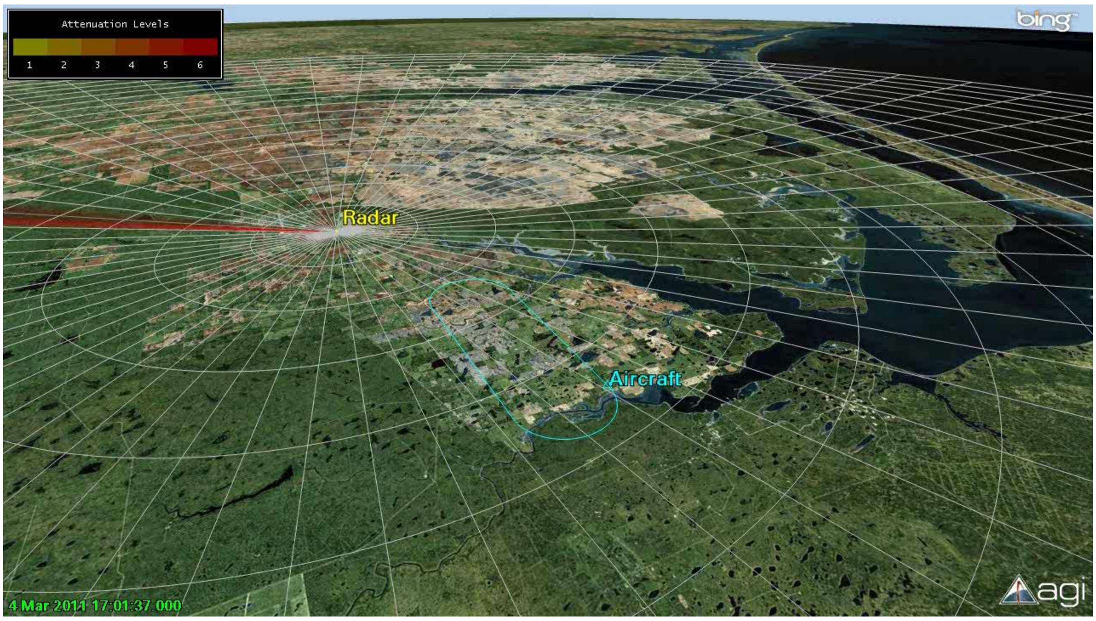


Figure 4.16 Terrain Flight pass/Airbase Analysis.

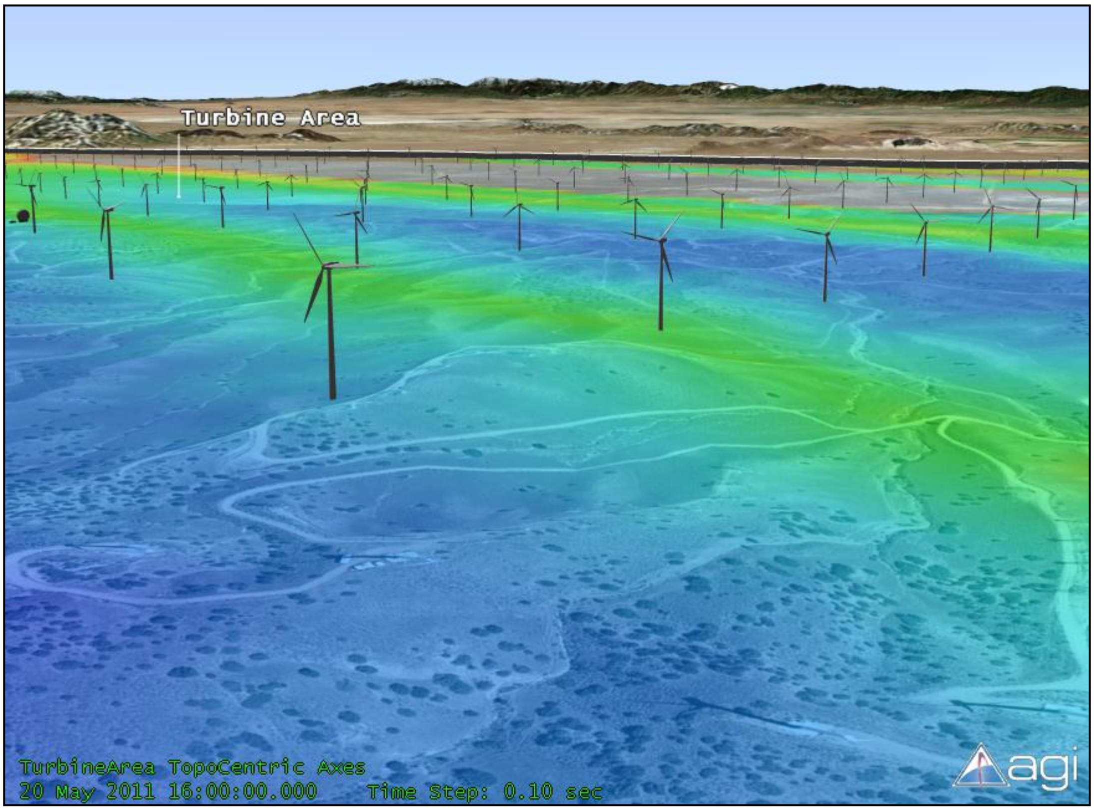


Figure 4.17 Close look at one of the wind farms used in simulation.

5. RESULTING EFFECTS

5.1 Yaw Angles of Turbine Blades

RCS with 90^o yaw angle to the radar creates the bigger interference. For radar operating at 3 GHz the RCS is steady around 58 dB, whereas, RCS changes from 52 dB to 57 dB with 0o yaw angle to the radar.

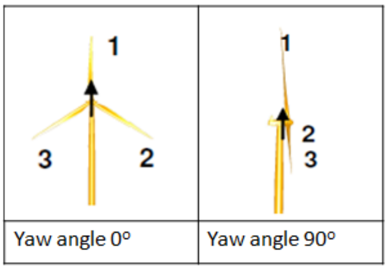


Figure 5.1 : Yaw angles from the perspective of radar.

Clutter occurring when yaw angle is 0^o can be filtered with classical methods such as Moving Target Indication. The situation of 90^o yaw angle over limits these classical methods and needs to be dealt with improved methods such as Doppler analysis.

5.2 Shadowing

When it is a wind turbine case, the partial shadow area increases, and the total shadow area is a blind region for radar.

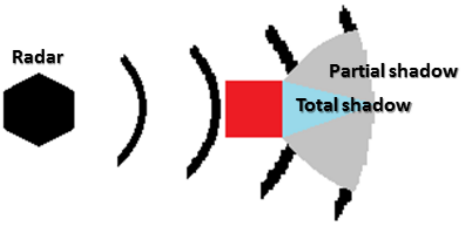


Figure 5.2 : Blind regions occurring behind the clutter source.

5.3 The Distance Between Sites

The distance between the wind power plant and the radar has the biggest impact (Barton, 1977).

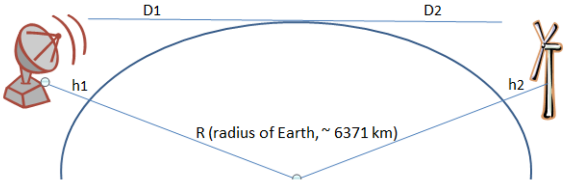


Figure 5.3 : Effect of geography

If the win power plant and the radar site are far enough from each other, the interference can be neglected.

Using Pythagorean Theorem:

$$D_i = \sqrt{(R + h_i)^2 - R^2} \approx \sqrt{2Rh_i} \quad \textbf{(5.1)}$$

where:

D_i is the distance between the objects tangent to the local horizon of a smooth round Earth,

R is the radius of the Earth,

h_i is the height of the object above mean sea level.

Let us assume h1 is 15 m and h2 is 91 m, multiply R it with 4/3 because of the refractivity of the atmosphere, we get;

$$D_i \approx 55.28\, km$$

which means that there will be negligible effect of a wind turbine on a radar if they are approximately 55.28 km apart from each other.

5.4 Turbine Coordinates

Turbines may also reflect signals on each other and if they are so close to each other this effect will increase. In such case, radar may not be able to correctly detect turbines’ coordinates.

5.5 Radar Equation

Classic radar equation (Barton, 1978):

$$R = \sqrt[4]{\frac{P_S G^2 \lambda^2 \sigma}{P_E (4\pi)^3}} \qquad \textbf{(5.2)}$$

where:

R is range (m)
P_S is the transmitted power (W)
G is the antenna gain
σ is the RCS of clutter (m^2)
λ is the wavelength (m)
P_E is the received power at the radar antenna (W).

As the RCS of a clutter increase the range decreases so false range readings occur at the radar display.

5.6 Power Reduction

For a target at point p which is located in the shadow region of the turbine, the decibel reduction in the power of the radar return is:

$$\begin{matrix} Power\ reduction \\ of\ radar\ return \end{matrix} = 40 \log \left(1 - \sqrt{\frac{D_{tp} S^2}{D_{tw} D_{wp} \lambda}} \right) \qquad \textbf{(5.3)}$$

where:

D_{tp} is the distance from the transmitter to a point p
D_{tw} is the distance from the transmitter to the wind turbine
D_{wp} is the distance from the wind turbine to a point p
S is the typical width of the wind turbine

Let us assume that the radar operating at 2.8 GHz is 5 km away from a wind turbine with a width of 3 m and there is a target located 15 km away from the wind turbine inside its shadow region.

$$\boldsymbol{\lambda = \frac{c}{f_{radar}} = \frac{3 \times 10^8}{2.8 \times 10^9} \frac{m/s}{1/s} = 1.07 \times 10^{-1} m}$$

$$\boldsymbol{D_{tw} = 5 \times 10^3 m}$$

$$\boldsymbol{D_{tw} = 5 \times 10^3 m}$$

$$\boldsymbol{D_{tp} = D_{wt} + D_{wp} = 2 \times 10^4 m}$$

$$\boldsymbol{\begin{matrix} Power\ reduction \\ of\ radar\ return \end{matrix} = 40 \log \left(1 - \sqrt{\frac{2 \times 10^4 \times 9}{5 \times 10^3 \times 1.5 \times 10^4 \times 1.07 \times 10^{-1}}} \right)}$$

$$\boldsymbol{= 40 \log \left(1 - \sqrt{2.24 \times 10^{-2}} \right)}$$

$$\boldsymbol{= -2.8}$$

The time variation of the transmitted power would have the effect that the apparent RCS of the target would vary from pulse to pulse and from sweep to sweep. However, one can expect the RCS to vary anyway, because any motion of the target will bring different scattering centres within the target into and out of phase.

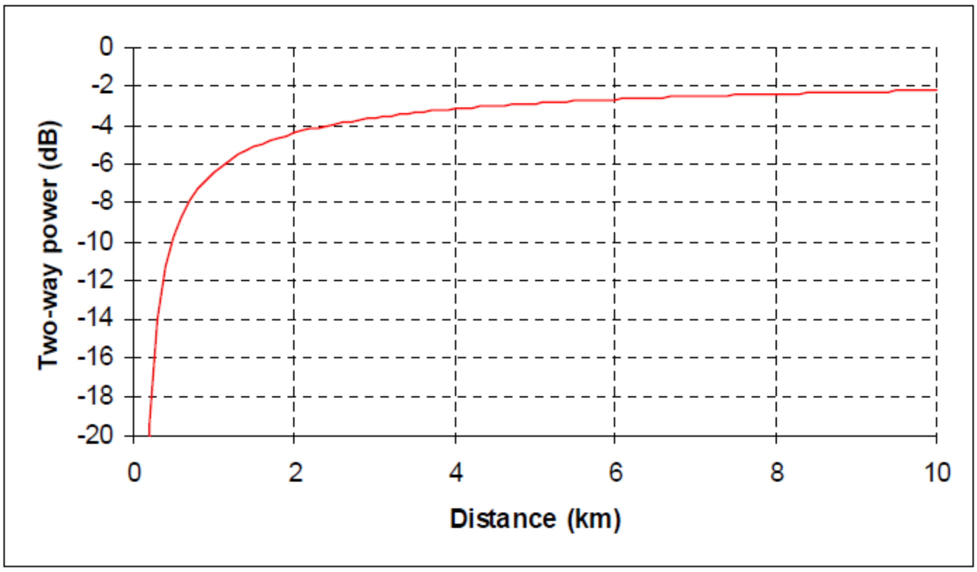


Figure 5.4 : Reduction in radar echo from point target behind 2 m wide obstacle (transmitter 18 km away, radar frequency 3 GHz).

Thus the turbine-induced variability does not itself make detection of the target by the radar more difficult than it is already. The average reduction in RCS over a cycle is quite small, unless the target happens to be precisely behind the turbine hub.

Figure 5.5 : Time variation of power behind rotating 50x3 m turbine blade (18 km to transmitter, 1 km to target; radar frequency 3 GHz).

5.7 Turbine Height vs Range

Wind turbine heights can reach hundreds of meters. This results in large RCS and potential for detection at long ranges.

5.8 The Rotor Diameter

With rotor diameters between 40 m and 120 m spinning at 10 to 35 rounds per minute, blade tip velocities can look like a desired target such as an aircraft or weather.

5.9 Damage to Radar Receiver

Radars' receiver protectors prevents damage from strong reflected signals, however standard upper limit is 53dB. Wind power plants constructed very near the radar (within a radius of 3 km) have the potential to return signals that exceed the limit of receiver protector and render the radar inoperable.

5.10 Why Not MTI?

All the body parts of a turbine and a bunch of turbine together in an area can block the beam of radar sight completely. The received power by the radar can be calculated as:

$$P_{rx} = \frac{P_{tx} g_{tx} g_{rx} \sigma \frac{\lambda^2}{4\pi}}{(4\pi d^2)^2} \tag{5.4}$$

which simplifies to

$$P_{rx} = \frac{P_{tx} g_{tx} g_{rx} \sigma \lambda^2}{64\pi^3 d^4}$$

where:

P_{rx} is the received power in W

P_{tx} is the transmitted power in W

G_{tx} is the transmitter antenna gain in dB

G_{rx} is the receiver antenna gain in dB

σ is the RCS of the turbine in m^2

λ is the wavelength of the operating frequency in m d is the distance between the radar and the turbine in m

The calculation of the radar receiver’s sensitivity is given by:

$$\text{noise floor (dBm)} = -174 + 10\log(B_{radar}) + NF \qquad \textbf{(5.5)}$$

where:

B_{radar} is the IF bandwidth of the radar in Hz
NF is the noise figure in dB

The highest I/N ratio permissible before radar performance degradation occurs is – 9 dB [13]. An I/N higher than – 9 dB may begin to adversely affect radar performance and cause loss of desired targets.

$$P_{thresh} = \text{noise floor (dBm)} - 9 \qquad \textbf{(5.6)}$$

For example, if the IF bandwidth of a given radar is 1 MHz and the noise figure is 5 dB, then the noise floor is (using equation 5.5):

$$\text{noise floor (dBm)} = -174 + 60 + 5 = -109\ \text{dBm}$$

The level (P_{thresh}) at which loss of targets will begin to occur is (using equation 5.6):

$$P_{thresh} = -109 - 9 = -118\ \text{dBm} = -148\ \text{dBW}$$

Let’s calculate what would be distance at which energy above the – 9 dB I/N threshold could enter the radar receiver via a sidelobe at 0 dBi gain for a radar with a transmit power of 1 MW and operating at 2.7 GHz. the calculation below is performed in MKS units using equation 5.4.

$$P_{tx} = 1\ \text{MW} = 10^6\ \text{W}$$

$$\text{Set } P_{thresh} = P_{rx} = -148\ \text{dBW} = 1.6\text{x}10^{-15}\ \text{W}$$

$$g_{tx} = g_{rx} = 0\ \text{dB} = 1$$

$$\lambda = \frac{c}{f_{radar}} = \frac{3 \times 10^8\ m/s}{2.7 \times 10^9\ /s} = 1.1 \times 10^{-1}\ m$$

For a typical wind turbine, $\sigma = 30$ dBsm $= 10^3\ \text{m}^2$

$$d = \sqrt[4]{\frac{P_{tx} g_{tx} g_{rx} \sigma \lambda^2}{64\pi^3 P_{rx}}} = \sqrt[4]{\frac{10^6 \times 1 \times 1 \times 10^3 \times 1.2 \times 10^{-2}}{2.0 \times 10^3 \times 1.6 \times 10^{-15}} m}$$

$$= \sqrt[4]{\frac{1.2 \times 10^7}{3.2 \times 10^{-12}} m = \sqrt[4]{37.5 \times 10^{17}} m = 4.4 \times 10^4 m}$$

It might be argued that the radar’s MTI processing will remove the display of effects due to scattered energy from a wind turbine farm. But here we are not considering the problem of displaying false targets generated by scattered energy from a turbine farm. Rather, we are considering the problem that energy scattered from a turbine farm will increase the effective noise floor of the radar receiver and hence cause desired targets to be lost. This effect cannot be mitigated by MTI processing.

Although the MTI processing will not eliminate effects that raise the noise floor of the radar, it will mitigate the display of false targets generated by scattered energy from a wind farm. However, it is possible that the radar’s MTI threshold will be exceeded by the Doppler shift from the spinning turbine blades. This will be the case if the maximum expected speed of the turbine blade tips exceeds the threshold speed of the MTI processing.

Nevertheless, the scattered energy that exceeds the MTI threshold is only a fraction of the total scattered energy (most of the energy is scattered from the stationary parts of the turbine and its supporting structure). If this fraction of the energy exceeds the radar noise floor and generates a false target, the total scattered energy is well above the -6 dB (or -9 dB) I/N thresholds discussed above. Thus, the criterion that no false targets be generated is much weaker than the criterion for no lost targets and will automatically be satisfied by the requirement for no lost targets. That is, if a wind turbine is close enough to a radar to produce a false target above the MTI threshold, then it is already close enough to exceed the radar’s I/N threshold for target loss, and hence is close enough to have caused the radar to have lost targets.

6. MITIGATIONS

There are two main ways of modifications. One of them is from radars' perspective and the other is from wind power plants' (Cain and Kirkwood, 2009).

6.1 Radar Mitigations

In old days, for old technology radars, ground fences were used around the radar area in order to cancel out the terrain reflections. But in wind farm case, this is a premature mitigation because of the heights in consider.

Figure 6.1 : Fences used to reduce interference from reflections (Hopwood, 2011).

1. Low frequency long-range radars can be used casting a wider area. But still turbines can have an impact on the transponder data.
2. The cost of a single radar installation is very much less than a single wind turbine construction. On the other hand, the cost of hundreds of wind turbines is very much higher. Under these circumstances, moving an impacted radar site to another place is much more efficient and cost effective (Barton, 1978).
3. When a wind farm has caused an unacceptable loss of coverage, supplementary gap filler radar could be installed.
4. Holographic radar systems can be used. A clutter map can be maintained for the stationary parts of a turbine on radar's memory. Processing over many scans

with radar memory in order to get the behavior of the moving target and see the changes clearly may help in defining the target.

5. Radars can look at higher elevations to see over wind farms, see Fig.10. But this can result in the loss of low- altitude information crucial in some forecast situations, such as a tornado.

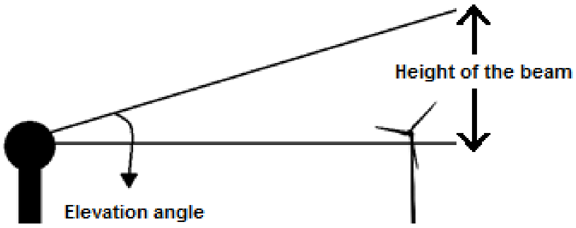


Figure 6.2 : Effect of elevation angle.

6. It would be hard to differentiate between wind turbines if there is more than one turbine in a radar resolution cell. That is why radar resolution should be higher if turbines are close to each other (Toskos, 2001).
7. Antenna with low side lobes or higher altitude radars can be used to reduce the effects of all ground clutter including wind farms. Only the main lobe can be the point of interest. But again, in this situation so many low altitude targets will be lost.
8. Multiple navigation radars, along with a centrally located high elevation scanning radar, sited within the wind farm, can provide improved elevation coverage above and around the wind farm itself.

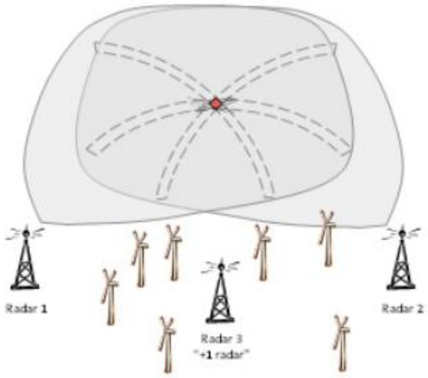


Figure 6.3 : Improved radar coverage over a wind farm.

6.2 Wind Power Plant Mitigations

1. Sudden change in the electrical property of the medium constitutes the target (conductivity, permittivity and permeability). Reduction of RCS by 99% about 20 dB is possible with stealth technology (Appendix B.1). However there will be a blind region for the radar behind the turbine. This may cause undesired results if there is a desired target in that region.
2. Wind farms can be constructed far from radar sites as far as possible. This brings two utilities:
    a. The greater the distance between the radar and the turbine, the shadow region will get smaller.
    b. If radar sites and wind power plants are far enough from each other, then because of Earth’s curvature there will be no ground data loss for radar readings and no interference with wind power plants. Because they will be under horizon, not in radar’s LOS.

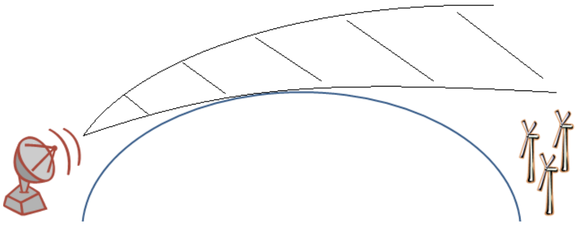


Figure 6.4 : Radar LOS oversees the wind power plant because of Earth’s curvature if they are located far enough.

3. Telemetry transmission can be used to supply real time data of wind turbines into radar system. This data can be determined according to the direction of the wind (because the change in wind direction affects the yaw angle of turbines) or can be supplied from the wind power plant control centre.
4. Construction of wind power plants can be restricted with law near defence or weather radar stations for the safety and security of the nation.
5. Multiple navigation radars, along with centrally located high elevation scanning radar, sited within the wind power plant, can provide improved elevation coverage above and around the wind farm itself.
6. Transponders can be used in wind power plant sites to supply signal info to the radars that will express its presence.
7. Turbines could be located in a way that the radar would only see one of them within its LOS. Turbines in a linear pattern can be preferred.

6.3 Both Way Mitigations

There will be no case like; a wind power plant and a radar site are constructed at the same time in a near-field area. If there is already a wind power plant in the area, then radar mitigations should be applied and if there is already a radar site in the area, then wind power plant mitigations should be applied.

7. CONCLUSIONS AND RECOMMENDATIONS

The wind power plants interfere with land radars. Short-term strategies consist of creating awareness of the problem, collaborating with other National Agencies and supporting experimental signal processing investigations.

Radar funding can lead to solutions such as development of modelling software that produces estimated radar impacts and signal processing technology that eliminates wind turbine clutter, building additional radars for an alternate view of impacted areas, building taller radar towers to see over wind turbines and moving existing radars to other locations. Besides, moving a wind power plant to another location is unlikely. Wind power plant funding leads to help developing radar-friendly, stealthy wind turbine blades and towers. However, the cost of making turbine blades almost invisible to a radar is 10% to 20% more than standard cost. The best solution might be to replace the aging radar stations with modern and flexible equipment that is more able to separate wind turbine clutter from desired objects. This would be a win-win situation.

The effects from individual turbines can add up linearly. However, the interactions can be random and chaotic sometimes. Multipath effects are worthy of further investigation. Due to multiple scatterings between more than one turbine and multipath effects, further radar performance degradation may occur, including overall noise level increase near the wind farm. Effects of wind power plants on mobile radars are complex situations, as well. This topic is worthy to investigate further. Software patches used to filter clutter out works better with offshore wind power plants, because there are less variables around. Wind turbine towers can be conic other than cylindrical. Never the less, the endurance of the design should be investigated.

The number of wind turbines closely correlates to the number of resolution cells affected, where turbine reflected energy signatures dominate those of target aircraft within a cell. The potential for false diminishes as turbines are moved further away from radar.

At best, we can ask questions like, “How many wind turbines are permissible?” and “How close is too close?” and the answers can determined by the operational needs at the affected radar site and the mitigation capabilities of the installed radar site.

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APPENDICES

APPENDIX A : Radar Cross Section
APPENDIX B : Stealth Technology

APPENDIX A : Radar Cross Section

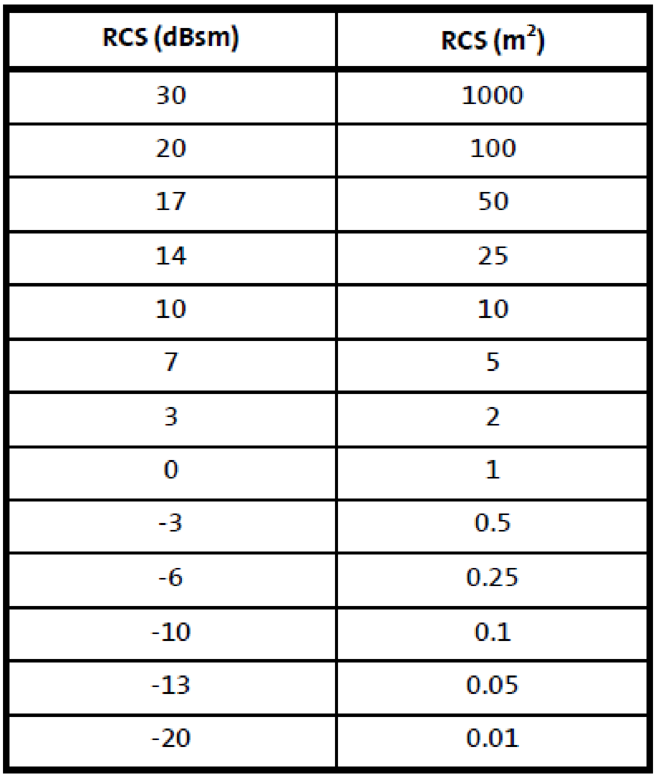
RCS (σ) = Geometric size × Reflectivity × Directivity

Geometric size: The frontal area that the object presents to the radar.

Reflectivity: A measure of the proportion of the incident energy that is reflected from the surface of the object. Energy that is not reflected is of course absorbed. Reflectivity also includes effects caused by induced electrical currents which cause re-radiation of the energy so is not exactly analogous to optical reflection.

Directivity: The shape of the surface of the object dictates the direction in which energy is reflected. Where the surface shape is curved, energy is concentrated into some directions and dispersed in other directions.

Table A.1 : Logarithmic RCS to linear RCS conversion table.



RCS (dBsm)	RCS (m^2)
30	1000
20	100
17	50
14	25
10	10
7	5
3	2
0	1
-3	0.5
-6	0.25
-10	0.1
-13	0.05
-20	0.01

APPENDIX B : Stealth Technology

Radar-absorbent material (RAM), often as paints, are used especially on the edges of metal surfaces. While the material and thickness of RAM coatings can vary, the way they work is the same: absorb radiated energy from a ground or air based radar station into the coating and convert it to heat rather than reflect it back. RAM may consist of ferrite paints or polymer layers incorporating crystalline graphite and it is possible that similar compounds are being employed. These types of RAM contain tiny spheres of material that oscillate as the radar waves hit them, ‘converting’ the radio waves into heat, which is then dissipated over the structure, rather than reflected.

Although such materials could also be used to coat the turbine blades, it is reported that this would add an extra 1.2 tonnes to the blades. Given that the entire rotor of a V90 turbine has a weight of around 38 tonnes, this would be a three percent increase on blade weight. Instead, the Vestas blades incorporate RAM consisting of two layers of glass-reinforced epoxy and plastic foam built into their structure, which reflect and absorb waves, reducing their cross section. Since these layers simply replace existing layers in the blades, there is reported to be little or no difference to the overall weight of the blade. According to Qinetiq, the cost premium is expected to be on the order of 10% of the overall cost of the blade.

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PUBLICATIONS/PRESENTATIONS ON THE THESIS

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