Impact Study of
130 Offshore Wind Turbines
In Nantucket Sound

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Executive Summary

This report examines the impacts to radar coverage from 130 proposed offshore wind turbines in Nantucket Sound.

Background

The FAA has three radars in the area surrounding Nantucket Sound. One long range radar, QEA, and two terminal radars for approach control to four airports. An Air Surveillance Radar-8 (ASR-8) at Otis Airfield (FMH) provides coverage for approach control into Hyannis Port (HYA), Martha's Vineyard (MVY), and Otis Airfield (FMH). An ASR-9 at Nantucket (ACK) provides coverage for approach control to Nantucket Memorial. The FAA provides approach control from the Cape Terminal Radar Approach Control facility (TRACON) at Otis Airfield. Two radar automation systems at the Cape TRACON provide live radar video to five Air Traffic Control (ATC) consoles. Each automation system is a Common Automated Radar Terminal Systems-2E (ARTS-2E). There is one ARTS-2E for the ASR-8 and one for the ASR-9.

Wind turbines can present a number of problems for radars. Wind turbines can obstruct the beam of the radar and block out a portion of the coverage volume. Wind Turbines can also reflect or distort the beam, causing false targets and speed jumps. Wind turbines present special problems for primary radar (search). Since radar returns from wind turbine blades share many characteristics with returns from aircraft, the radar processor treats them as if they are from aircraft. The results are primary clutter displayed on the ATC console, and aircraft returns being obscured by wind turbine returns. The ASR-9 has an automatic clutter control feature that lowers the sensitivity of the processor in areas of high clutter; resulting in very little clutter on the ATC display. A result is that the Probability of Detection (PD) decreases in the areas where sensitivity is lowered. Air traffic controllers will notice non-reinforced beacon over the wind farm and misses of primary only aircraft (aircraft without transponders).

Conclusions

Signal reduction behind the wind farm should have little or no noticeable impact on secondary radar (beacon). Signal reduction behind the wind farm should have little or no noticeable impact on primary radar (search). There is a strong likelihood for fading of beacon radar up to 2 nmi and primary radar up to 3 nmi behind the wind farm below an altitude of 600'. Traffic patterns suggest that aircraft do not fly below 600' near the proposed wind farm. There is a marginal possibility that fading of secondary radar could occasionally result in some missed or garbled replies below 1,000' over Nantucket for the FMH ATCBI-5 and below 1,000 over Otis from ACK Mode S. It is unlikely that these misses will impact air traffic operations. There is also a marginal possibility that fading of primary radar could impact primary coverage below 1,000' over Nantucket from FMH ASR-8, and coverage over Otis below 1,000 from ACK ASR-9. This could impact air traffic operations when ACK or FMH search radar is out of service.

Air traffic controllers will experience excessive clutter from the ASR-8. Reduced sensitivity of the ASR-9 over the wind farm will result in lower Probability of Detection (PD) for the ASR-9 over the wind farm. ASR-9 PD could drop as much as 10%, but ASR-9 PD is not expected to drop below acceptable values. Air traffic controllers will see some non-reinforced beacon and some primary only misses from the ASR-9 over the wind farm.

With the current configuration of the Cape TRACON automation systems, air traffic controllers are confined to using the ASR-8 exclusively for all approaches into HYA, MVY, FMH. The ASR-9 is used exclusively for all approaches into ACK. Currently there is no flexibility to use the ASR-9 and the ASR-8 where each offers the best coverage. This will be a disadvantage when tracking primary only aircraft over, or behind, the wind farm.

Recommendations

1. A TDX-2000 should be installed for the ASR-8 at FMH and optimized by the TDX-2000 National Ops Support group.
   Estimated Cost: $1.5 Million

2. The ARTS-2E associated with the ASR-8 should be modified to accept a digital input.
   Estimated Cost: To be determined

3. The Displays at the Cape TRACON should be upgraded to digital displays.
   Estimated Cost: To be determined

4. Common ARTS does not allow a sensor mosaic, but there may be upgrades or alternatives to the current configuration to increase the flexibility ARTS-2E. The Common ARTS Program Office and Common ARTS National Ops Support group should be consulted to determine if there are any upgrades or alternatives to the current configuration of the automation systems at the Cape TRACON. Any cost associated with these upgrades should be considered during negotiations with the wind power provider.

5. The high beam/low beam transition point should be place beyond the extent of the wind farm for each ASR.

6. Tech Ops should ensure that there are no performance problems with the ASR-8 or the ASR-9 prior to installation of any wind turbines.

7. Baseline recordings should be made for the ASR-8 and ASR-9 prior to the installation of any wind turbines. These recordings should be compared to recordings made after the wind turbines have been installed. These recordings should be made under different weather conditions during winter and summer. Data recordings with the ASR-8 can be made as soon as a TDX-2000 has been installed. In addition to data recordings, recordings with the Radar Analysis Support System (RASS) should be made. Any impacts from the wind turbines can be measured by a comparison of these recordings.

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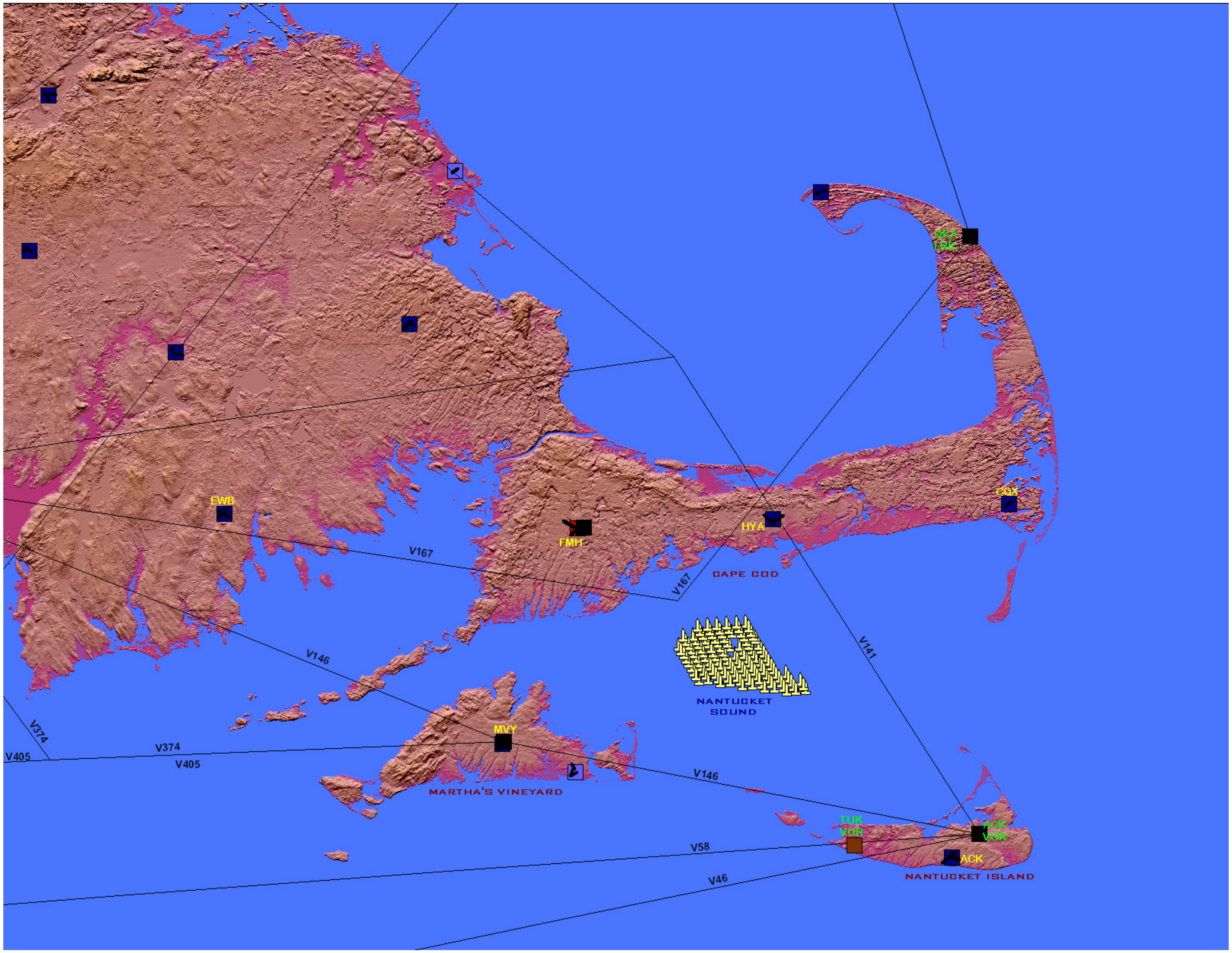


EWB
V167
FMH
HYA
CAPE COD
V167
QEA
LRR
CGX
V141
NANTUCKET
SOUND
V146
MVY
V374
V405
V374
V405
MARTHA'S VINEYARD
V146
TUK
VOR
ACK
VOR
ACK
NANTUCKET ISLAND
V58
V46

Figure 1

Scope

This report focuses on the likely impacts that a proposed large wind farm in Nantucket Sound would have on Federal Aviation Administration (FAA) radar coverage for the area.

Introduction

Nantucket Sound is the body of water in Massachusetts that lies between Cape Cod, Martha's Vineyard and Nantucket Island. In 2006, Cape Wind Associates proposed erecting 130 wind turbines in Nantucket Sound, and submitted an Obstruction Proposal form-7460 to the FAA for each wind turbine. The wind farm would encompass over 35 square miles of Nantucket Sound. At that time, the FAA issued a determination of no hazard regarding all 130 wind turbines. **Figure 1** shows a map including the proposed wind farm 6 miles South of Hyannis. The map shows the four airports, a number of smaller airfields, and pilot navigation aides. Navigation aides are radio frequency (RF) beacons that guide pilots along particular vectors called victor airways, which are like highways in the sky. The victor airways associated with Nantucket Sound are also shown. **Figure 2** shows a close-up of Nantucket Sound, and the location of the wind farm including distances to the four airports and some victor airways.

Wind turbines placed near radars can impact radar coverage and performance. As with any large metal tower placed near a radar, wind turbines can obstruct a radar's view of the coverage volume, and deform or reflect the radar's beam to cause speed jumps and false targets. But the characteristic that differentiates wind turbines from other obstructions is the rotating blades. Air search radars are designed to look for fast moving objects in the sky, and wind turbine blades can often meet these requirements. Wind turbines are mounted on tall towers, and are often placed high on ridges. The blades can be 140' long, and the blade tips can reach speeds in excess of 150 knots. Often, a radar processor can not discriminate between an aircraft and a wind turbine blade. As a result, wind turbines can obscure aircraft that fly over them. Returns from rotating wind turbine blades are processed and displayed like returns from aircraft and display as clutter on ATC consoles. Largely due to concerns over the possibility of impacts to radar coverage, the FAA has agreed to reexamine the Cape Wind proposal. During this process, the FAA Western Service Area Tech Ops Surveillance Engineering Branch was asked to study the potential impacts that the wind farm would have on radar coverage and performance for the area. This study was accomplished using software modeling tools and empirical evidence not available in 2006.

The proposed wind power project lies in Nantucket Sound 6.5 miles South of Hyannis, 5.6 miles Northwest of Martha's Vineyard and 10 m North of Nantucket Island

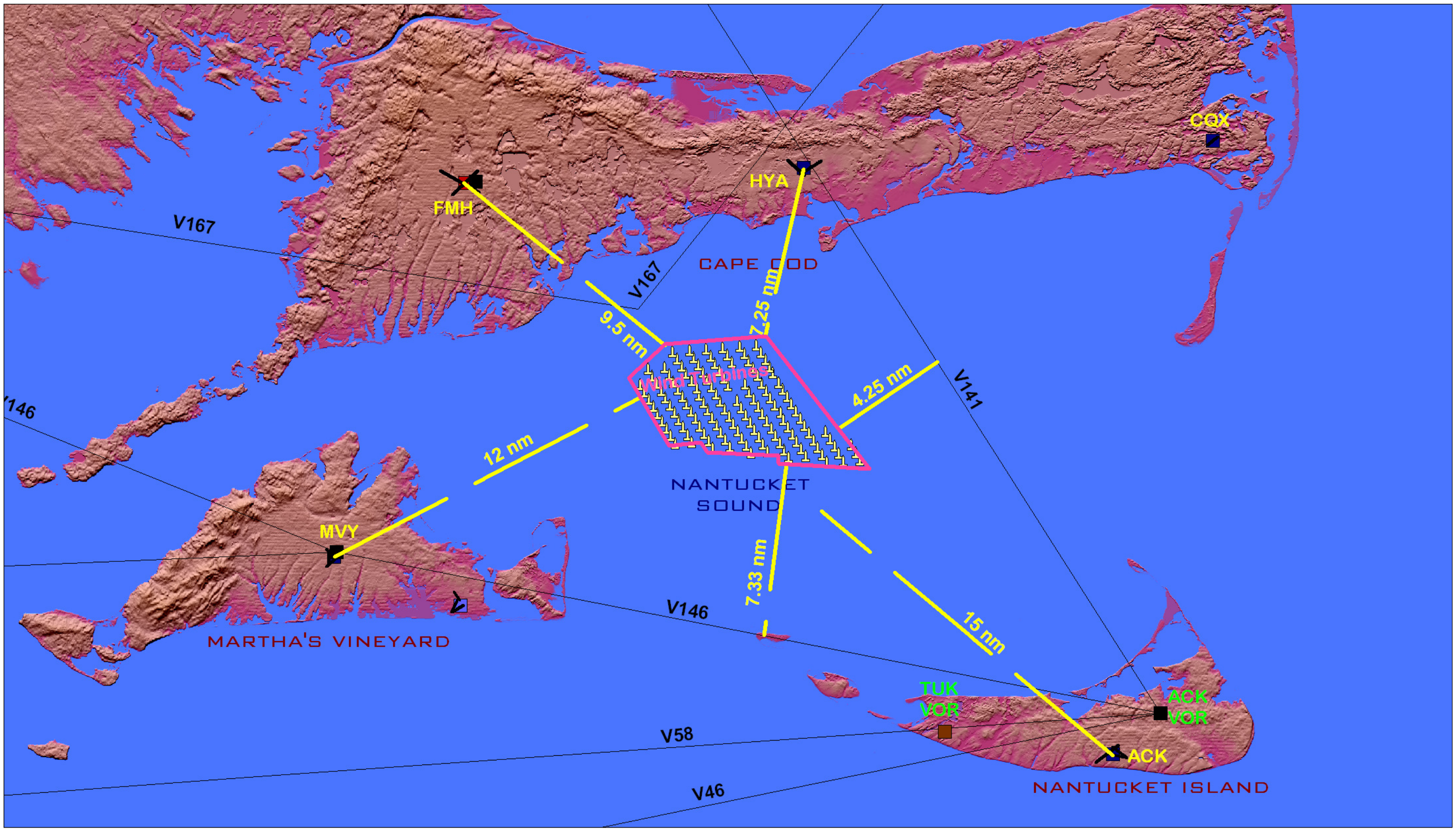


Figure 2

The area around Nantucket Sound is serviced by three airports and a number of small air fields. The three airports are Barnstable Municipal in Hyannis (HYA), Nantucket Memorial on Nantucket Island (ACK), and Martha's Vineyard (MVY). The FAA maintains a small Terminal Radar Approach Control (TRACON) facility at Otis Airfield in Falmouth, MA on Cape Cod for the purpose of approach control to the four airports. Radar coverage for the TRACON is provided by two terminal radar facilities with supplemental coverage from a long range radar facility.

Table 1 Nantucket Radar Facilities

3-letter ID	**FMH** (same as associated airport)	
Location	Otis Airfield (former AFB),Falmouth, MA	
Search Radar	Terminal Air Surveillance Radar	
ASR-8	Moving Target Filter	moving target integrator (MTI)
	Post Processing	None
Beacon	Air Traffic Control Beacon Interrogator	
ATCBI-5	Operational Mode	Air Traffic Control Radar Beacon (ATCRB)
	Processing	None
Output	Quantized Video	
Use	approach control into Hyannis Port (HYA), Martha's Vineyard (MVY), and Otis FMH	

3-letter ID	**ACK** (same as associated airport)	
Location	Nantucket Memorial Airport, Nantucket Island, MA	
Search Radar	Terminal Air Surveillance Radar	
ASR-9	Moving Target Filter	moving target detection (MTD) digital Doppler
	Post Processing	tracker, dynamic geocensor, beacon reply processor,
		beacon false target elimination, beacon/search merging
Beacon	Monopulse Beacon System	
Mode S Beacon Interrogator	Operational Mode	mode select roll call with low-duty cycle ATCRB
	Processing	tracker, mode select roll call, false target elimination,
		degarbling, beacon / search target merging
Output	Digital Target Messages	
Use	approach control into Nantucket Memorial (ACK)	

3-letter ID	**QEA**	
Location	North Truro, MA	
Search Radar	Air Route Surveillance Radar, Long Range 3-D Height Finding	
ARSR-4	Moving Target Filter	moving target detection (MTD) digital Doppler
	Post Processing	tracker, beacon reply processor,
		beacon false target elimination, beacon/search merging
Beacon	Monopulse Beacon System	
ATCBI-6	Operational Mode	mode select roll call with low-duty cycle ATCRB
	Processing	tracker, mode select roll call, false target elimination,
		degarbling, beacon / search target merging
Output	Digital Target Messages	
Use	Enroute Air Traffic Control and National Defense	

QEA provides data to the Air Route Traffic Control Center (ARTCC) in Boston as well as the Air Force Eastern Defense Sector. QEA also sends beacon only data from the QEA ATCBI-6 for use during CENRAP (Center Radar Arts Presentation). CENRAP is only used for approach control when both FMH and ACK beacon radars are out of service. When air traffic controllers use QEA for approach control, the minimum separation of aircraft must be increased

- The target update rate from the long range radar is 12sec instead of 4.2sec due to a slower antenna rotation rate.
- CENRAP is beacon only and no search coverage is provided

Most Air Traffic Control Services provided to pilots by the ARTCC are reserved for aircraft equipped with transponders. Sometimes ARTCC controllers provide some services to aircraft on approach to non-radar equipped airports with instrument approaches. For these services, search radar coverage at low altitudes is desirable. Within the coverage volume of QEA, there are many terminal radars that send data to Boston ARTCC to provide low-altitude search coverage: Nantucket (ACK) ASR-9, Providence (PVD) ASR-9, and Boston (BOS) ASR-9. For these reason, the impacts from the proposed wind farm to the low-altitude coverage of the ARSR-4 search radar are not as critical to the mission of the FAA. Potential impacts to the QEA ARSR-4, therefore, will not be treated as rigorously in this report as impacts to the two terminal radar facilities that feed the Cape TRACON.

In the Cape TRACON at Falmouth, there are two Common Automated Radar Terminal-2E Systems (Common ARTS-2E). The ARTS-2E performs some processing functions, associates beacon codes with flight plans and tail numbers, and distributes search and beacon data and video to the Air Traffic Control (ATC) consoles. The ARTS-2E can be configured to accept analog video or digital target messages. One ARTS-2E systems at the TRACON receives video from FHM ASR-8 / ATCBI-5 and distributes target video and decoded beacon replies to the three ATC consoles used for approach control into HYA, MVY and ACK. The other ARTS-2E receives data from the ACK ASR-9 / Mode S and distributes data and video to the two ATC consoles used for approach control into Nantucket.

Data and Analysis

Initial analysis of the Cape Wind farm involved Radar Support System (RSS). RSS is a software package for radar siting developed by Technical Services Corporation (TCS) for the FAA. The FAA uses RSS for coverage analysis of future and current radar sites. The components for a particular site include USGS terrain data and existing or proposed buildings surrounding the site. A single site can encompass the entire coverage volume of a long-range radar. RSS contains models of various radars including the ASR-9, the ASR-8, and the ARSR-4. These models include characteristics and variable parameters for the transmitter, receiver, antenna, processor and the environment for each model. Depending on the model, variable parameters may include antenna type, location (Lat/Long), tower height, weather conditions, transmit frequency, transmit power, noise figure, Doppler filter coefficients and refraction index of the atmosphere. Some of the models, such as the ASR-9 and the ARSR-4, include a wind turbine analysis tool. Since the ASR-8 doesn't include a wind turbine analysis tool, the ASR-9 was substituted for FMH for the wind turbine analysis portion of the RSS study. The following types of plots were generated for this report using RSS:

1. Line of Sight
2. Range Azimuth Probability of Detection for a $1m^2$ aircraft at a specified altitude

Line Of Sight (LOS)

Line of Sight (LOS): Uses terrain and 4/3 Earth's radius as well as cultural data, when available, to determine lowest elevation MSL visible by range/azimuth for the coverage volume of the radar. The earth's effective radius is a variable parameter.

A Nantucket site data base was created in the RSS using terrain data downloaded from the USGS Seamless server. No buildings were included in the analysis. Three antenna positions and their respective antenna tower elevations were included in the data base. The wind turbine analysis tool doesn't include all of the post processing functions radar. For example, ASR-9PAC-II and tracker and geocensor functions are not part of the RSS model. Signal integration over coherent processing intervals is included in the ASR-9 model. Nine different receiver beam patterns in the vertical plane are included in the ARSR-4.

First, Line of Sight (LOS) plots were generated for the each of the three antenna positions: QEA, ACK and FMH. The plots revealed that all three positions have line of sight to the proposed wind farm. QEA will see the top 100' – 150' of most of the wind farm; 3 – 4 wind turbines will not be visible to QEA. The ASR-9 at Nantucket, with a feed horn height of 76' MSL, will be able to see nearest wind turbine down to 12' above the water. The Mode S array is mounted above ASR-9 reflector. This slight height advantage allows the Mode S at ACK to see the nearest wind turbine 6' above the water. The Mode S Antenna will have visibility to most of the wind farm above 111' MSL.

Line of Sight Plots for ACK using RSS

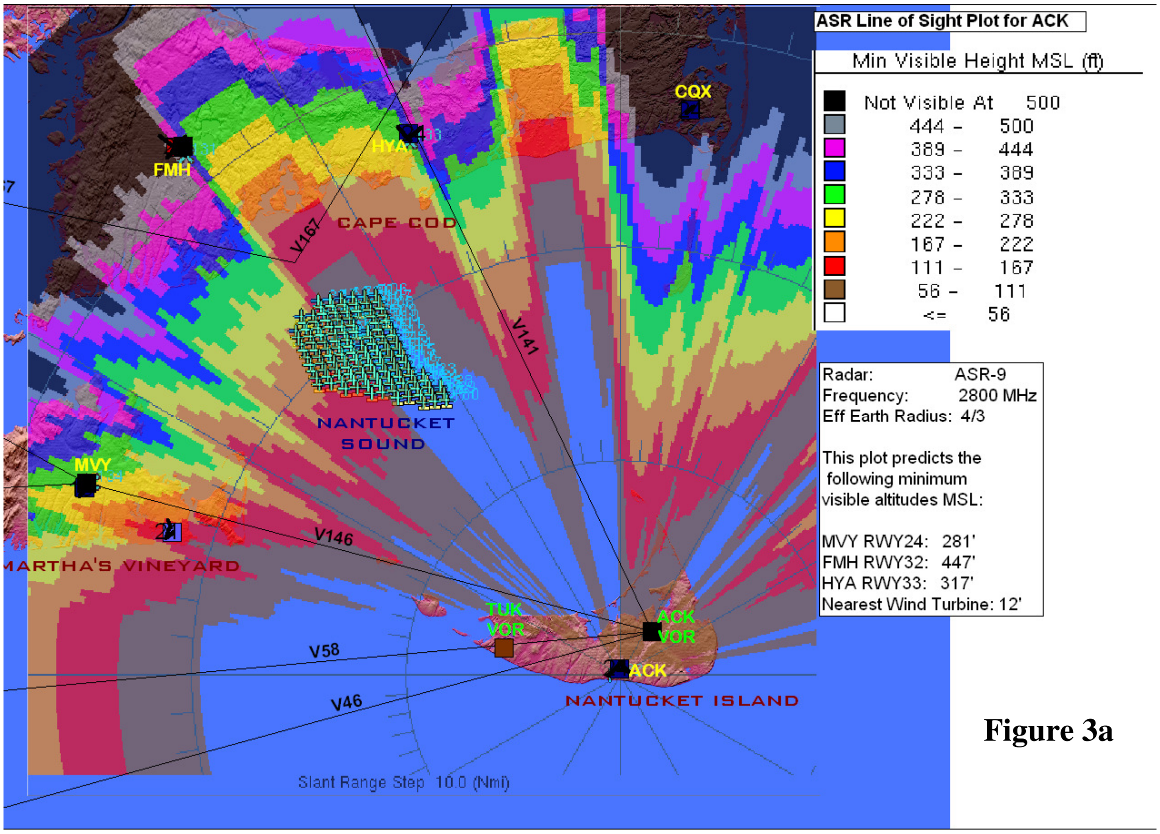


Figure 3a

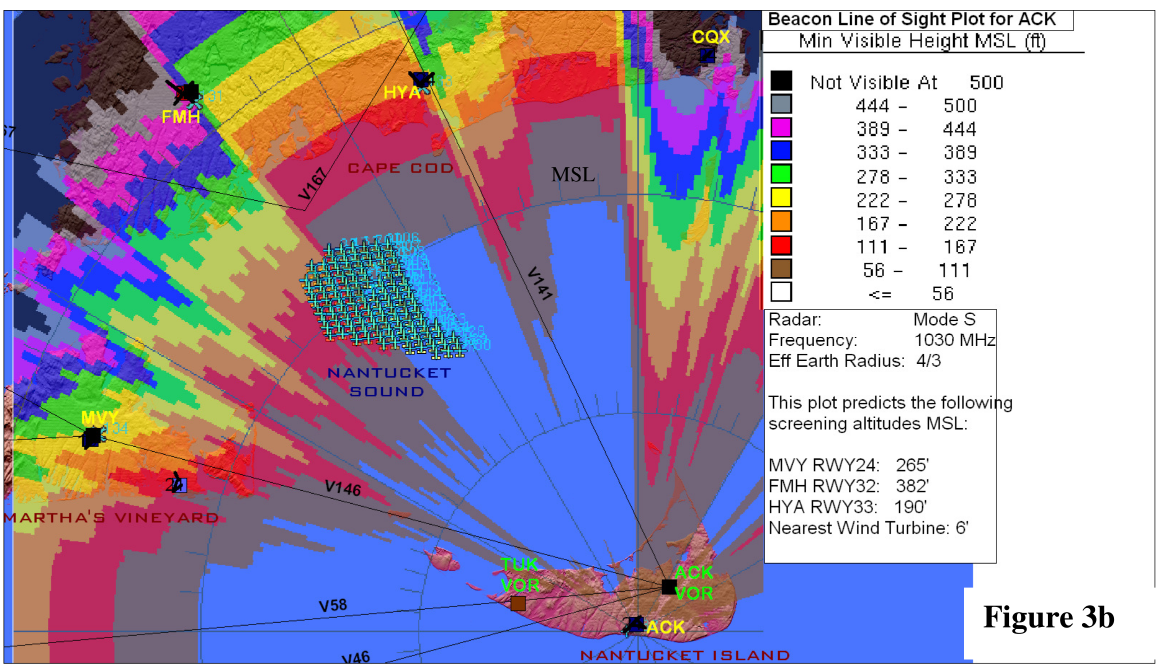


Figure 3b

Figure 3a,b show the line of sight (LOS) visibility to the wind farm for the ACK ASR-9 and Mode S. The minimum visibilities above the runways at MVY, FMH and HYA as well as the minimum altitude visible at the nearest wind turbine are shown.

The ASR-9 has LOS to the entire wind farm, and visibility throughout the wind farm varies from 12' above the water to 250' above the water. The Mode S antenna is mounted 8' above the ASR antenna. This height advantage allows ACK Mode S to see down to 152 MSL' above Hyannis Runway 33, whereas the ASR-9 can see down to 317 MSL' (HYA RWY 33 has a ground elevation of about 40'MSL).

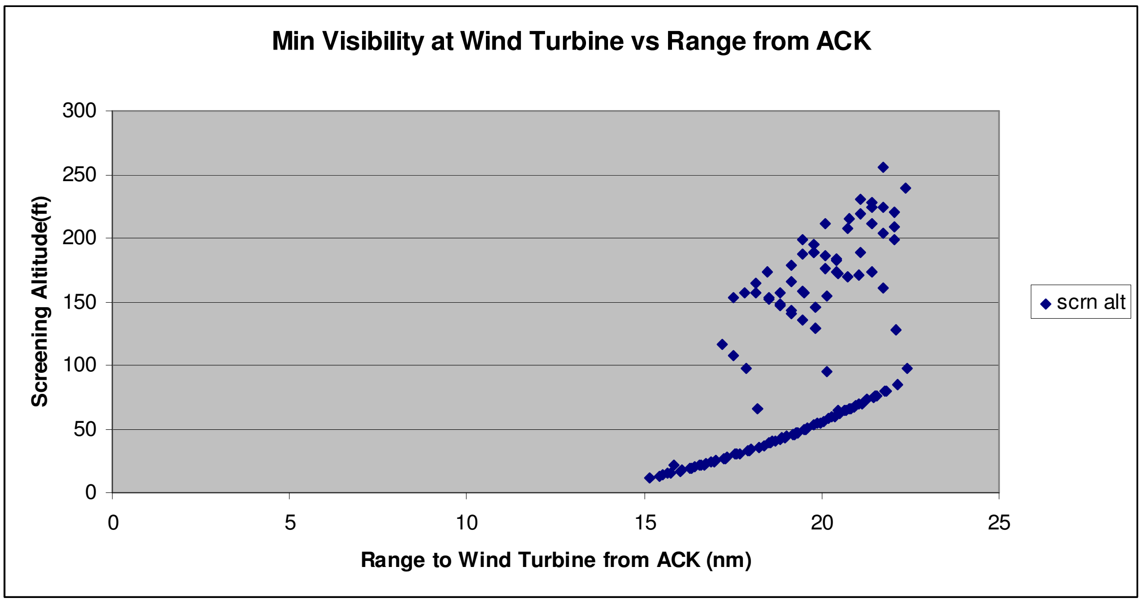


Figure 4

Figure 4 shows the predicted screening altitudes to each wind turbine with respect to range from ACK. The anticipated height of the wind turbines to the tip of an upright blade is 440'. It is clear from this the distribution in figure 17 that ACK will have line of sight to all the wind turbines. More than ½ of the wind turbines are visible below 150' off the water.

Line of Sight Plot for FMH using RSS

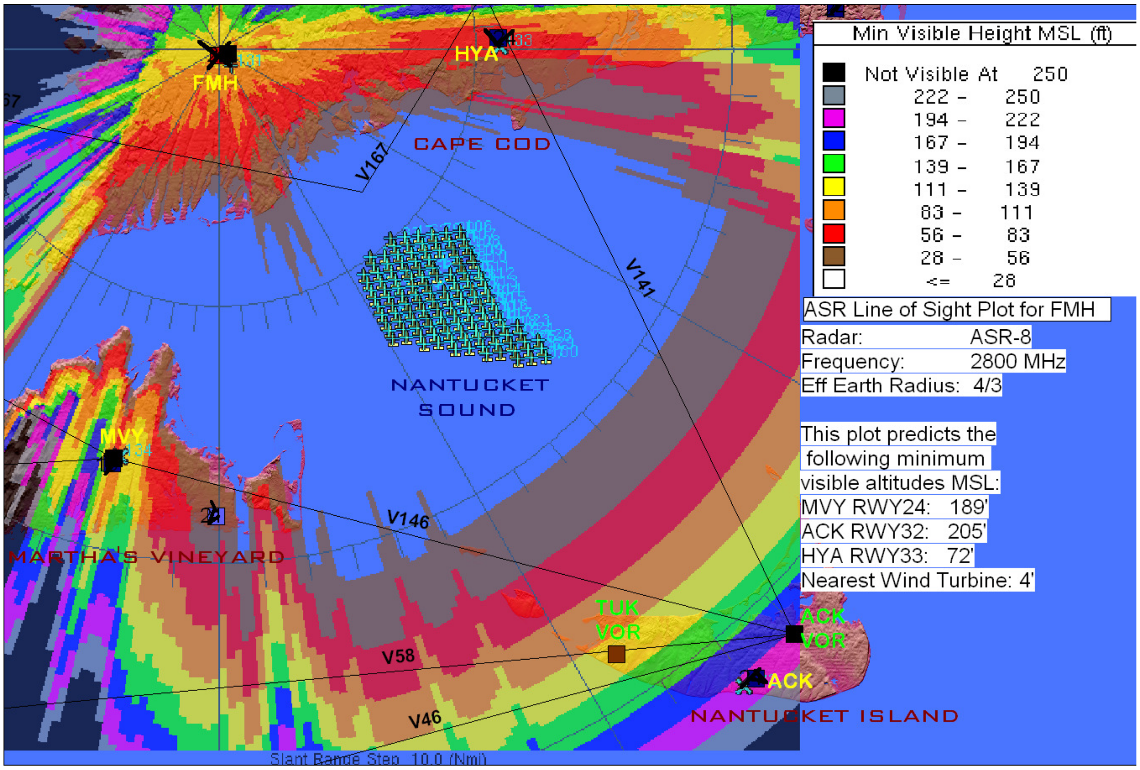
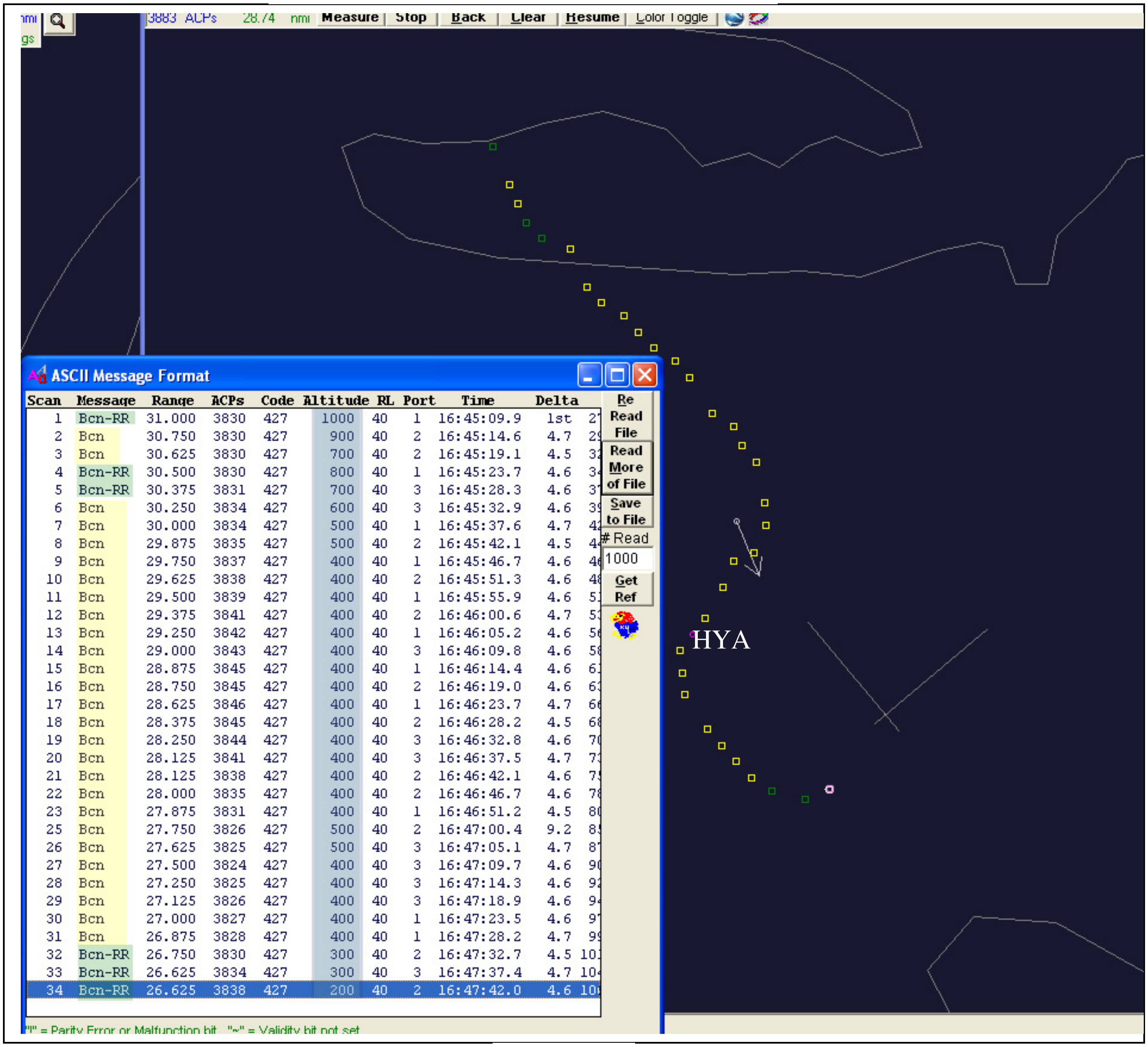


Figure 5

Figure 5 shows the RSS predicted coverage for FMH ASR-8. The feed horn elevation for FMH is nearly 70'MSL above that of ACK. As a result, the coverage volume drops down a little lower over MVY and the wind farm. FMH ASR-8 can see most of the wind turbines down to 10' off the water.

Validation of LOS Plots with Real Data



Scan	Message	Range	ACPs	Code	Altitude	RL	Port	Time	Delta
1	Bcn-RR	31.000	3830	427	1000	40	1	16:45:09.9	1st
2	Bcn	30.750	3830	427	900	40	2	16:45:14.6	4.7
3	Bcn	30.625	3830	427	700	40	2	16:45:19.1	4.5
4	Bcn-RR	30.500	3830	427	800	40	1	16:45:23.7	4.6
5	Bcn-RR	30.375	3831	427	700	40	3	16:45:28.3	4.6
6	Bcn	30.250	3834	427	600	40	3	16:45:32.9	4.6
7	Bcn	30.000	3834	427	500	40	1	16:45:37.6	4.7
8	Bcn	29.875	3835	427	500	40	2	16:45:42.1	4.5
9	Bcn	29.750	3837	427	400	40	1	16:45:46.7	4.6
10	Bcn	29.625	3838	427	400	40	2	16:45:51.3	4.6
11	Bcn	29.500	3839	427	400	40	1	16:45:55.9	4.6
12	Bcn	29.375	3841	427	400	40	2	16:46:00.6	4.7
13	Bcn	29.250	3842	427	400	40	1	16:46:05.2	4.6
14	Bcn	29.000	3843	427	400	40	3	16:46:09.8	4.6
15	Bcn	28.875	3845	427	400	40	1	16:46:14.4	4.6
16	Bcn	28.750	3845	427	400	40	2	16:46:19.0	4.6
17	Bcn	28.625	3846	427	400	40	1	16:46:23.7	4.7
18	Bcn	28.375	3845	427	400	40	2	16:46:28.2	4.5
19	Bcn	28.250	3844	427	400	40	3	16:46:32.8	4.6
20	Bcn	28.125	3841	427	400	40	3	16:46:37.5	4.7
21	Bcn	28.125	3838	427	400	40	2	16:46:42.1	4.6
22	Bcn	28.000	3835	427	400	40	2	16:46:46.7	4.6
23	Bcn	27.875	3831	427	400	40	1	16:46:51.2	4.5
25	Bcn	27.750	3826	427	500	40	2	16:47:00.4	9.2
26	Bcn	27.625	3825	427	500	40	3	16:47:05.1	4.7
27	Bcn	27.500	3824	427	400	40	3	16:47:09.7	4.6
28	Bcn	27.250	3825	427	400	40	3	16:47:14.3	4.6
29	Bcn	27.125	3826	427	400	40	3	16:47:18.9	4.6
30	Bcn	27.000	3827	427	400	40	1	16:47:23.5	4.6
31	Bcn	26.875	3828	427	400	40	1	16:47:28.2	4.7
32	Bcn-RR	26.750	3830	427	300	40	2	16:47:32.7	4.5
33	Bcn-RR	26.625	3834	427	300	40	3	16:47:37.4	4.7
34	Bcn-RR	26.625	3838	427	200	40	2	16:47:42.0	4.6

Figure 6

Using WinPlot, **Figure 6** is a playback of 34 scans of ACK during July 4th 2008. The data shows a plane with ID 427 on descent into HYA RWY6 from the North along V141. Green squares indicate Reinforced Beacon, yellow squares indicate Beacon only. Text output of the data for scans 1-34 is shown on the left. Notice search radar loses the plane at scan 6 when, as the altitude column shows, the plane dropped below 600'MSL. The search radar sees the plane for the last 3 scans south of the runway. The ASR9 likely spotted the plane at scan 30, but the ASR-9 tracker must wait for 3 updates to output a mature target. Neither Beacon or search saw the plane below 200'. A close look at the LOS plots for ACK (**Figure 6**) will show that this data supports the RSS prediction.

Probability of Detection (PD)

Probability of Detection is a prediction of the likelihood that the radar will identify a target at a particular location. PD is a quantitative predictor of radar performance for a given coverage volume. A probability of .9 (90%) or better is desirable. For most search radars, a PD of .8 (80%) or better is considered satisfactory. The probability of detection (PD) for the entire coverage volume of a radar is an important consideration when determining criteria for a radar installation such as location, tower height, and antenna tilt. RSS considers terrain, ground cover, effective earth's radius, proposed or existing buildings, environmental conditions, radar cross section and radar parameters to calculate probability of detection for the proposed coverage volume of a radar. For radar models that include the wind turbine analysis tool, the RSS also takes into account the positions and size of wind turbines along with the speed and direction of the wind. RSS doesn't factor in many post processing functions of the ASR-9, such as the tracker or the 9PAC-II dynamic geocensor. For all the PD plots generated for the proposed Cape Wind Project, environmental parameters were selected to provide high winds blowing in a direction that would result in the worst case orientation of the wind turbines with respect to each radar-under-test. This aspect angle is from the side of the wind turbine to maximize the amplitude and Doppler content of the wind turbine blade returns. As an example, for ACK and FMH, the winds were from the Northeast or the Southwest. The model assumes that the wind turbines face the wind and have a maximum rotation rate, but no cut-out speed.

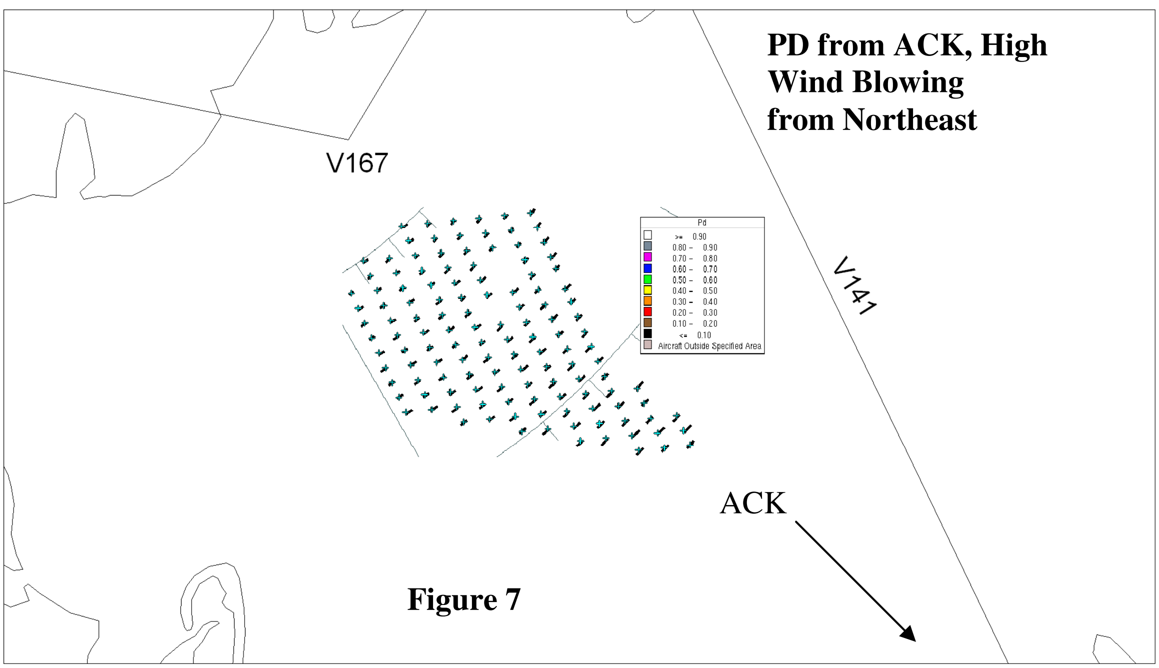


Figure 7 shows a plot of predicted PD over the proposed wind farm for ACK ASR-9. Each cyan X represents the position of a wind turbine. Each black rectangle over each X indicates that the probability of detection approaches zero over each wind turbine. The dimensions of each black rectangle are equal to the processing resolution of the ASR-9 radar: 1.4° azimuth X 1/16 nmi range. This plot affirms that the ASR-9 will not be able to detect targets above a wind turbine if the blades are rotating fast enough with a

sufficient component of radial motion toward the radar. The PD in F**igure 7** is for an aircraft flying at 1,000' MSL. Successive plots at other altitudes under the same wind conditions yielded identical results for the ACK ASR-9.

PD from ACK, Low Wind
Blowing Form Northwest

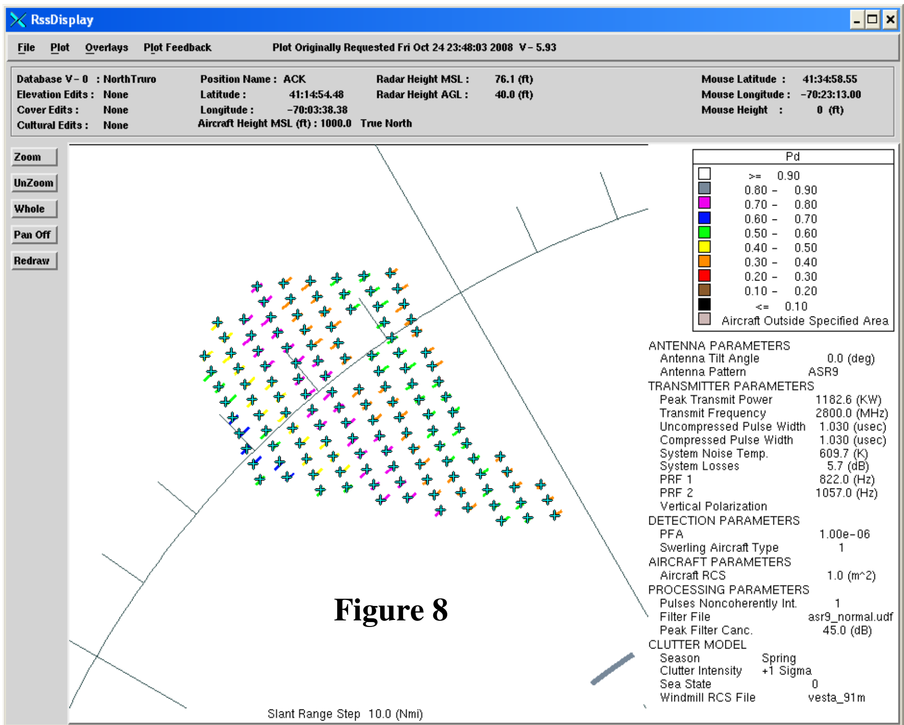


Figure 8

Figure 8 is a PD plot for ACK with the wind speed at 2 knots blowing from the Northwest. Note that PD is still impacted for a 1m^2 target. Experience has shown that this is not likely to be the case if the motion of the blades is mostly tangential.

The RSS ASR-8 siting analysis tool doesn't have a wind turbine function, so the ASR-9 model was used to analyze FMH for PD. RSS gave the same prediction for PD over the wind farm for FMH as for ACK. If the blades are moving with a large radial component with respect to the radar, detection over each wind turbine will approach zero.

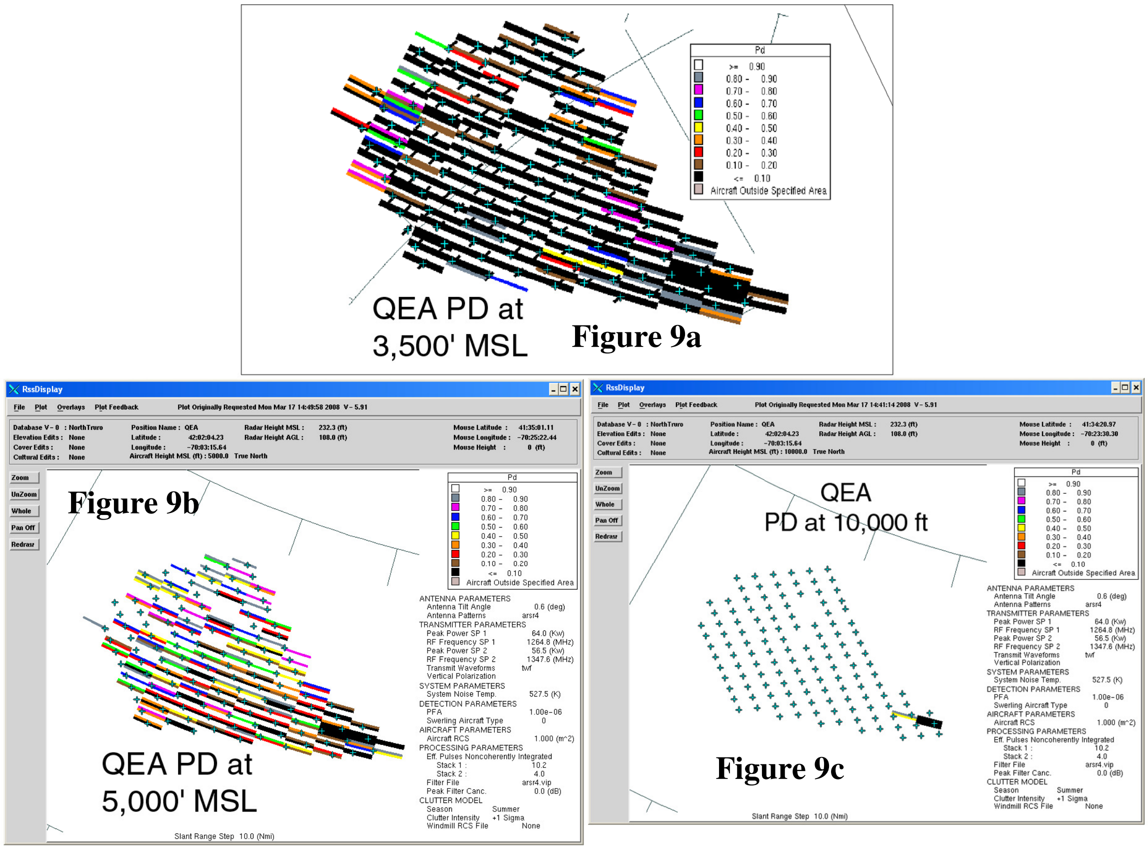


Figure 9

Figure 9a,b,c shows 3 PD plots for QEA generated using RSS. QEA is an ARSR-4 long range 3-dimensional height finding search radar. In order to determine height of a target, the ARSR-4 receives echoes from a vertical stack of 9 different beams at two different frequencies. Each beam at each frequency has an independent receiver. Echoes from aircraft flying very low over the wind farm will have the greatest amplitude in the receiver for the lowest beam. Coverage in the lowest beam will be similar to that of the 2 ASRs except the resolution of the processing wedges will be wider in azimuth because the ARSR-4 is farther away from the wind farm. The slice in **Figure 9a** is at 3,500' MSL. Although most of the volume over the wind farm is impacted due to the wider azimuth extent of the processing wedges, the PD is >0 for much of the wind farm. **Figure 9b** shows marked improvement of PD at 5,000' MSL. **Figure 9c** shows that there is almost no impact from the wind turbines to the ARSR-4 search radar at, or above, 10,000' MSL.

Figure 10 shows a real recording of radar video from an ASR-8 while 6 wind turbines within 2 nmi faced the radar directly such that the motion of the blades relative to the radar was almost purely tangential.

ASR-8 RASS Video Recording of Aircraft Flying over Wind Turbine with Tangential Blade Motion

Normal Video **MTI Video**

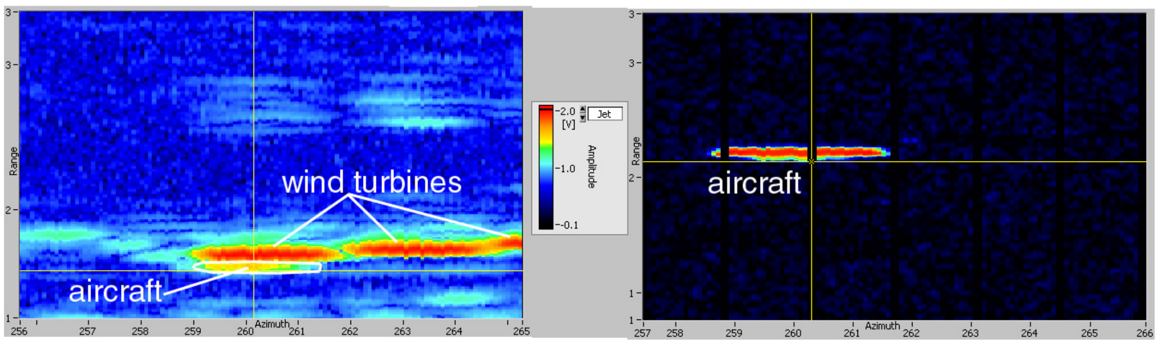


Figure 10

Figure 10 shows screen shots from a Radar Analysis Support System (RASS) video recording from an ASR-8 at Great Falls, MT as a flight check aircraft flies directly over a wind turbine about 2 nmi from the radar. The vertical scale is range (nmi) and the horizontal scale is azimuth (deg). The RASS simultaneously records two channels of the receiver output. In the video recording presentation, video amplitude (volts) is designated by color, and the scale is shown in the center of the **Figure 10**. This recording was made using the normal operating STC curve. The screen shot on the left is from a recording of normal video, which includes all returns and noise and interference. The screen shot on the right is from a simultaneous recording of MTI video from the moving target integrator filter. The output of the MTI filter is only moving target video, which includes moving targets and any very large amplitude stationary targets that exceed the sub-clutter visibility of the MTI Filter (break-through clutter). Each screen-shot is from the same range, azimuth window during the same instant in time – a single PRT (transmit-receive cycle). There is a slight time delay for MTI filtering results in a slight range delay in the MTI presentation. In the normal video screen-shot, there is a thin white circle drawn around the aircraft (yellow), which is smaller in amplitude than the echo from the wind turbine it is about to fly over (bright red). In the screen-shot on the right, there is no sign of the wind turbine at the output of the MTI filter, and only the aircraft is visible. The wind was blowing along a radial between the radar and the wind turbines. This means that the hubs of the wind turbines were pointed right at the radar and all six wind turbines were facing the radar directly like sunflowers facing the sun. With that orientation, the motion of the blades was almost purely tangential. That is why there is no evidence of the wind turbine blades in the MTI channel and why returns from the blades do not obscure returns from the aircraft.

Shadowing

The mathematical model discussed in **Appendix B, Shadowing**, was used to predict the impact to radar coverage due to wind turbines. Most of the modeling was focused on FMH.

- FMH is closest to the wind farm by 2 nmi.
- According to the LOS plots, FMH ASR-8 has the best view of the wind turbines, therefore it seems likely that the wind farm would be a greater obstruction to coverage from FMH.
- FMH ASR-8 is the only radar that will see a significant amount of traffic at an altitude where screening is possible. When ACK ASR-9/Mode S is completely out of service, FMH is used for approach control into Nantucket. Parts of the approaches to Nantucket are directly behind the wind farm from the perspective of FMH.

For a single wind turbine 10 nmi from the radar, the model predicted severe impacts below 500' to beacon for ½ nmi behind the wind turbine, and up to 3 nmi for the search. The model predicted moderate impacts to beacon for 1.5 nmi behind the wind turbine, and up to 5 nmi for search. Traffic patterns do not indicate traffic in these areas below 500'. The model was also used to determine the impact from overlapping shadows at the ranges that FMH would likely see low flying aircraft. The model predicted that there would be no impact to the beacon due to overlapping shadows. The model predicted that there could be an impact to search due to overlapping shadows at the range of the approaches to Nantucket. The model predicted that narrow regions could exist where up to 4 shadows overlap resulting in up to 10 dB of attenuation along these narrow wedges. This very conservative model is based on worst case assumptions for effective shadow width and for uniformity of attenuation across the shadow. The prevailing model for shadowing suggests that the center of the shadow is the darkest part of the shadow. From the center toward the extent of the effective shadow width, the shadow transitions from maximum attenuation to zero attenuation at the rate of a sinc function (sin(x)/x). This implies that the narrow wedge of 10 dB of attenuation at the range of the approaches Nantucket is *not realistic*. Based on the model and on the geometry, the shadows could overlap to create wedges of up to 5 dB of attenuation. It is likely that such wedges would have a small impact on search PD behind the wind farm up to a couple of percentage points. The vertical extent of the shadowing is predicted to be up to 1,500' MSL at the range of Nantucket. This also involved a very conservative approach as the entire wind farm was modeled as a huge metal building as tall as a wind turbine with the blade pointing straight up. In reality, any impacts would most likely be observed low in the beam where antenna gain is low and where the towers and nacelles obstruct the radar LOS. This would be the case below 900' over Nantucket from FMH.

The FAA and the Air Force conducted a wind turbine impacts flight test at Great Falls, MT, where there is a single row of wind turbines 2 nmi from the radar. The equipment at Great Falls was configured simulate the equipment at FMH. The shadowing model predicts noticeable impacts out to about 2 nmi. Shadowing effects were observed out to about 2nm. No shadowing impacts were observed beyond 2 nmi.

Models for Shadowing in Nantucket Sound

The shadowing function used for the analysis in this report is the same function discussed **Appendix B – Shadowing B6**. A derivation for the function is given in Reference [1a]. The following analysis considers a 5 meter diameter tower placed 10 nmi from a radar. This geometry would most closely resemble the closest wind turbine to FMH. The radar parameters used are identical to those discussed in shadowing section of Appendix B.

Attenuation Behind a Wind Turbine

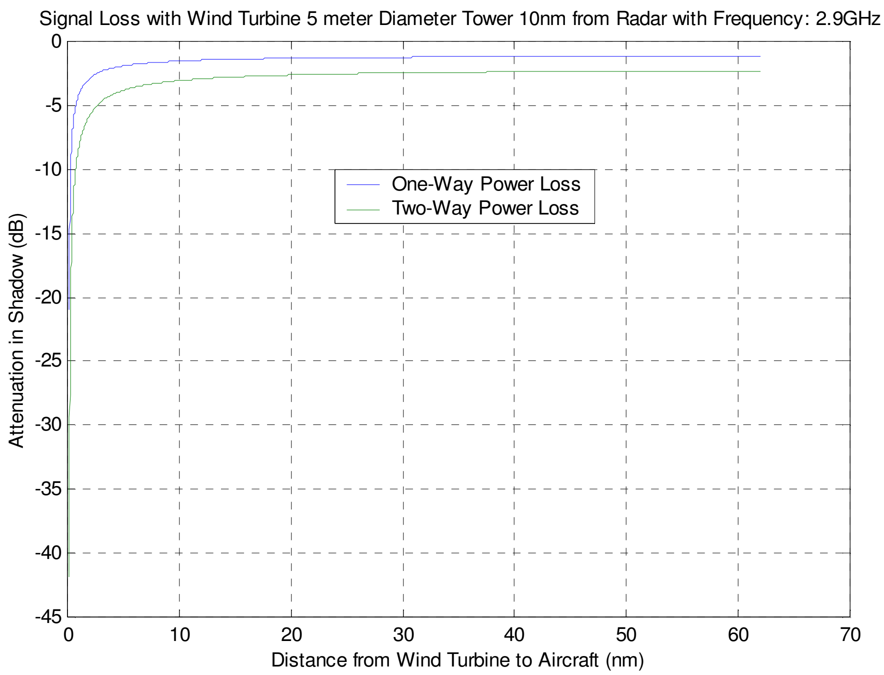


Figure 11a

Figure 11a,b was developed using the same equations discussed earlier in this report. This plot shows the signal reduction in the shadow of a wind turbine. The horizontal scale begins .15 nmi behind the wind turbine and gives the distance from the wind turbine to an aircraft flying through the shadow. The vertical scale represents signal reduction in the shadow. Both one-way and round-trip attenuation are shown. **Figure 11a** predicts that the round-trip attenuation will approach a constant value of 2.4dB. This could impact marginal targets near the MDS level of the radar, especially during inclement weather. Marginal targets include those near maximum range or very low in the beam.

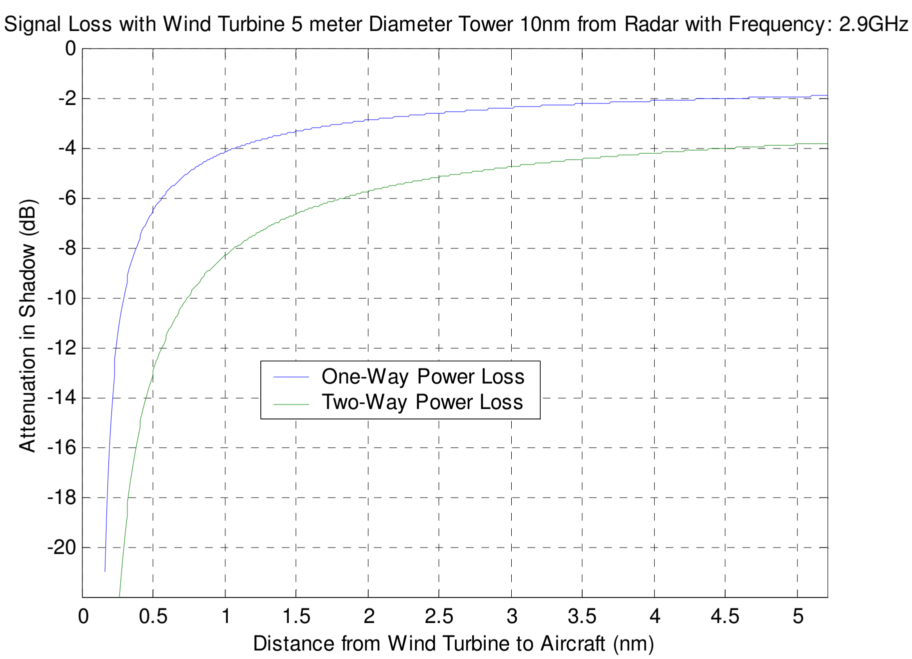


Figure 11b

Figure 11b shows a close-up of signal reduction in the first 5 nmi and reveals that the shadow is very dark for the first 1/2 nmi behind the wind turbine, and fairly dark for the first 2 nmi behind the wind turbine. After 2 miles, illumination in the shadow begins to level off toward the asymptotic value of 2.4dB of attenuation.

Power in Search Receiver

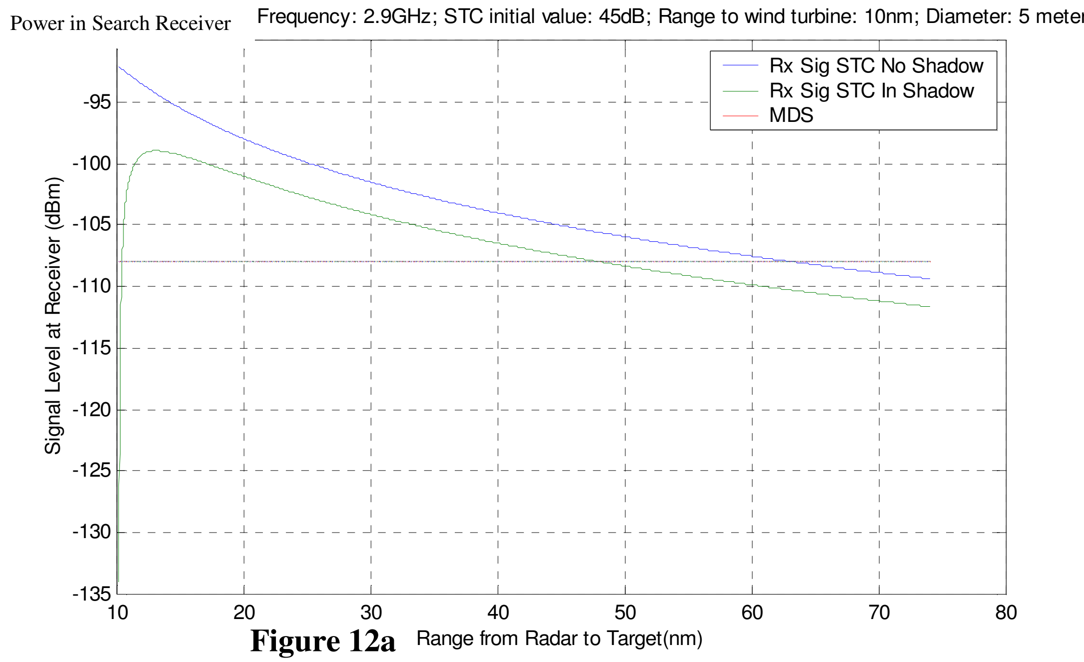


Figure 12a

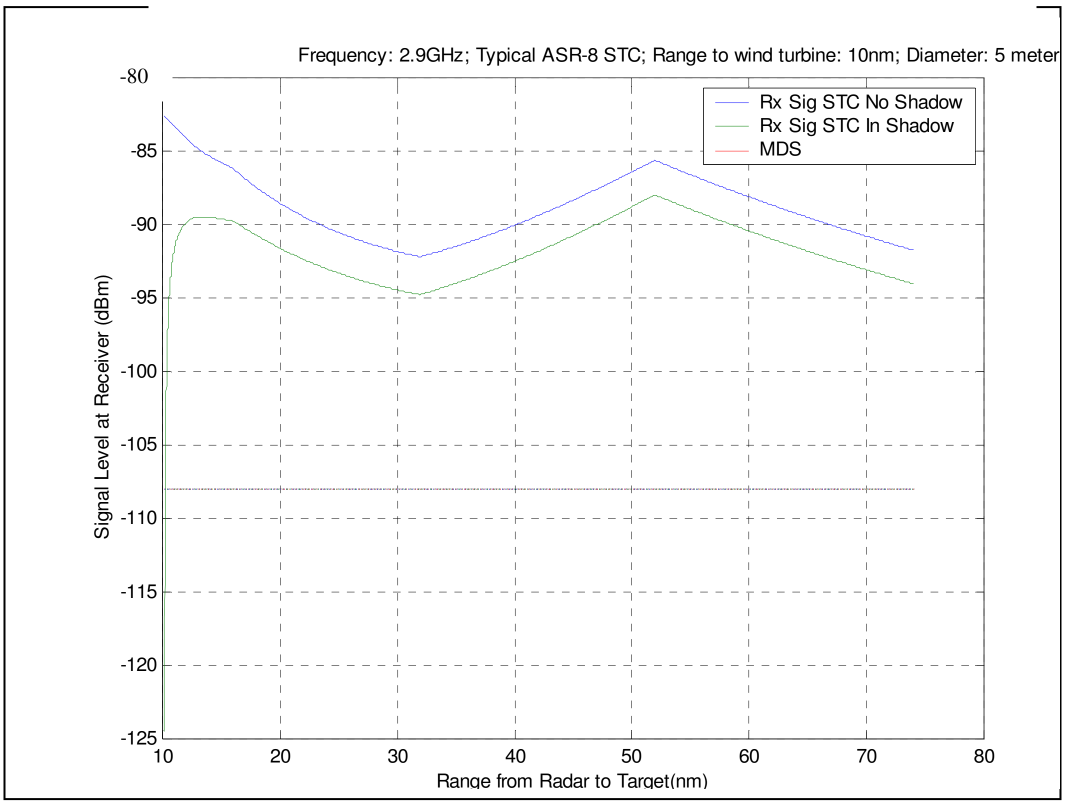
Figure12a shows the power of an echo at the radar receiver from a 1m^2 target as range to the target increases from 10 nmi to 70 nmi. This plot was generated based on a 45dB initial value, non-recovering, 20dB/decade STC beginning at 1 nmi. The STC curve was chosen so that the power level in the receiver from an echo of a 1m^2 target at a range of 60 nmi in the nose of the beam and with no atmospheric attenuation, would equal -108dBm, the MDS of the ASR-9. This function does not accurately model the performance of the ASR-8/9, but uses the radar equation and some easily known ASR-8/9 parameters. The blue line in the plot represents the power in the receiver from a target with no wind turbine. The green line represents the power received from the same target in the shadow of a wind turbine located 10 nmi from the radar. This plot demonstrates that echoes from an aircraft in the shadow of a wind turbine could be reduced by as much as 2.5dB. This attenuation could push marginal targets below the MDS of the receiver, especially during inclement weather. Marginal targets include those near the end of maximum range or low in the beam.

It is important to point out at here that a typical ASR-8 STC curve begins at 24dB and has a slope of 6dB/octave. At sites with high levels of clutter, an initial value of 36 dB might be used with a slope of 9 dB/octave. An STC curve with an initial value as high as 46 could be temporarily selected during conditions of very high clutter. The ASR-8 STC curve generally recovers around 20nm. At the minimum, this would raise the curves in **Figure 12** by **10dB**. This would raise a target at MDS in **Figure 12a** to 8dB above the MDS.

Figures 13a,b have been added to give an idea of how the model behaves using realistic STC curves. The ASR-9 curve in **Figure** 13**a** is based on a figure in the ASR-9 technical manual titled ***Typical ASR-9 STC Curve***. The factory default STC curve recovers at

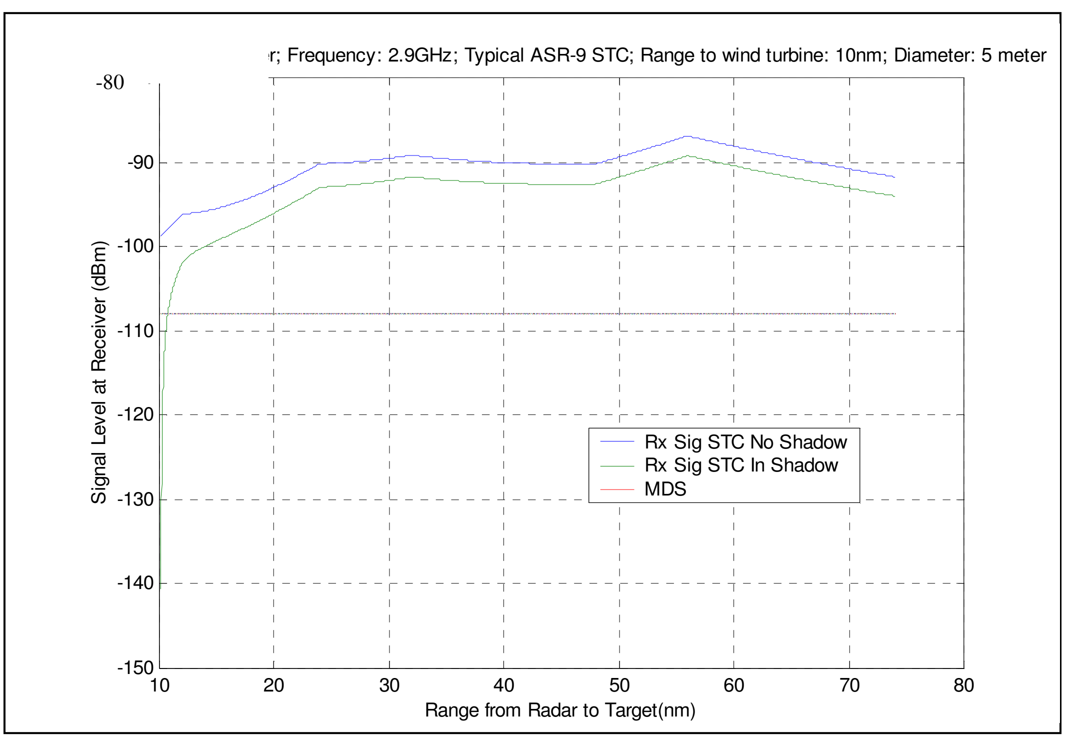
16nm, the curve used for **Figure 13b** recovers at 52nm. A typical ASR-8 STC curve also recovers around 20nm. For **Figure 13b**, a curve with a high initial value that recovers around 55nm was used. **Figures 13a,b** demonstrate that when STC recovers before maximum range, there is more power at the receiver from targets near maximum range. **Figure**s **13a,b** show that, power in the receiver from a target at MDS in **Figure 12** (previous page) is 18dB above MDS using STC curves that recover before end of range.

Power of an Echo in Search Receiver with Realistic STC



ASR-9

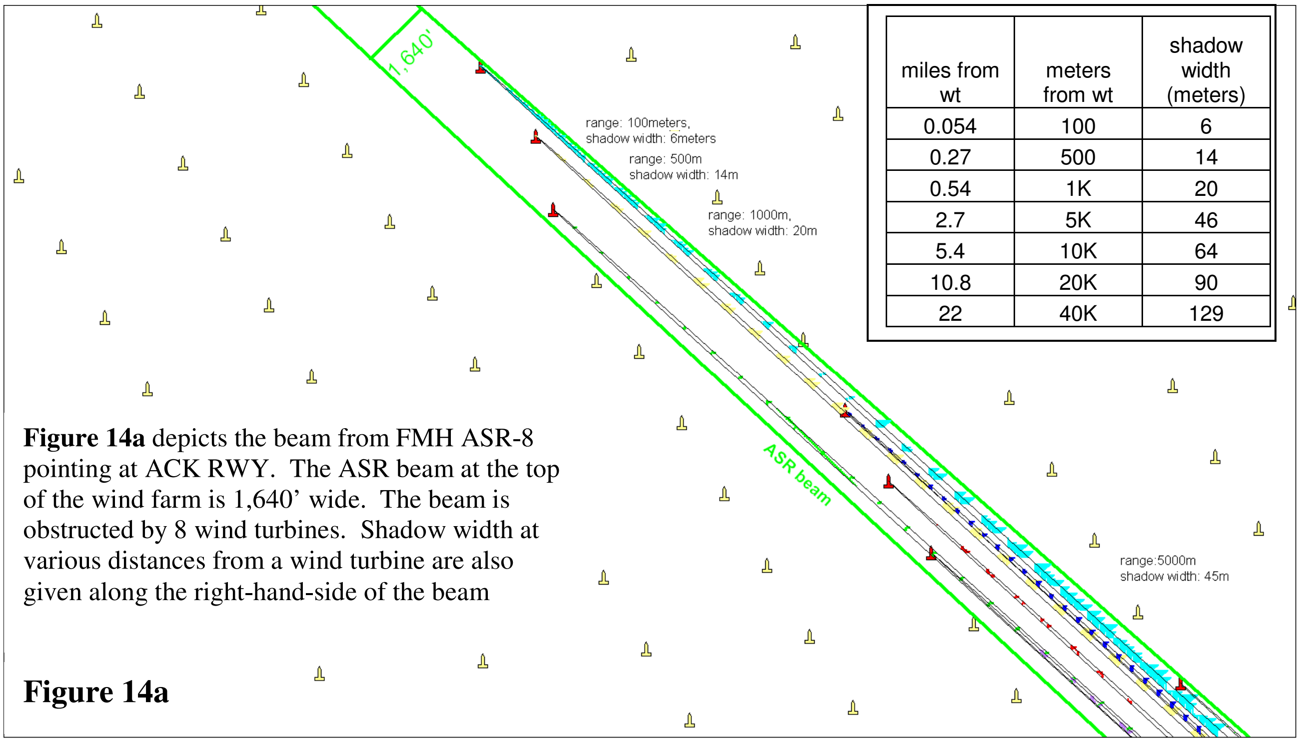
Figure 13a



ASR-8

Figure 13b

Shadows Beacon on ACK Runway from Wind Turbines Illuminated by FMH



miles from wt	meters from wt	shadow width (meters)
0.054	100	6
0.27	500	14
0.54	1K	20
2.7	5K	46
5.4	10K	64
10.8	20K	90
22	40K	129

Figure 14a depicts the beam from FMH ASR-8 pointing at ACK RWY. The ASR beam at the top of the wind farm is 1,640' wide. The beam is obstructed by 8 wind turbines. Shadow width at various distances from a wind turbine are also given along the right-hand-side of the beam

Figure 14a

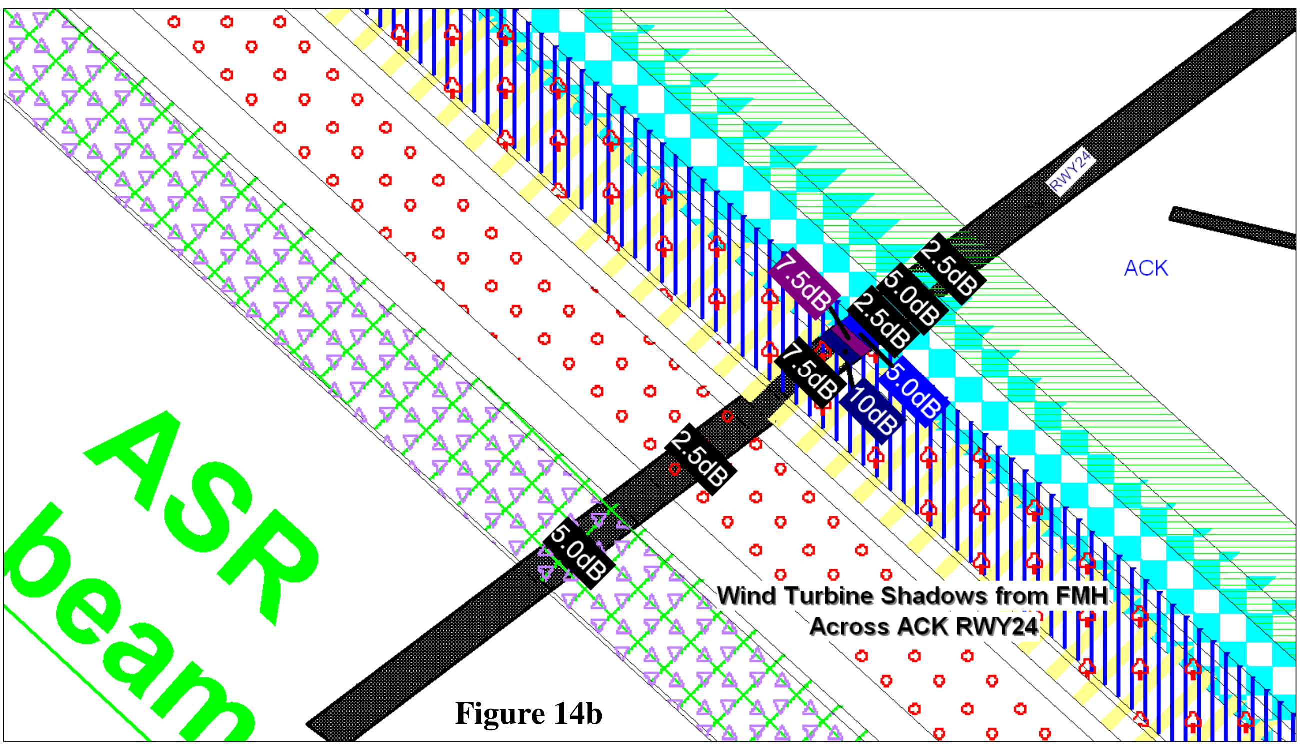


Figure 14b

Figure 14b depicts the 8 shadows over ACK RWY 24. The calculated attenuation within each shadow at this range is about 2.5dB. Where shadows overlap, the worst case combined effect would be the attenuation of a single shadow squared. On a logarithmic scale, the attenuation where shadows overlap= (2.5dB)*(number of shadows). Labels of estimated values are distributed across the runway. It should be noted that the values given in **Figure 14** are based on an assumption that the shadow is uniform across the effective width. According to the model used for this report, the shadow would actually be darkest (2.5dB) only at the very center. Toward the edges, the shadow becomes brighter according to a Sinc function. (**Appendix B - Shadowing**)

Attenuation Behind a Wind Turbine 10 nmi from a Radar

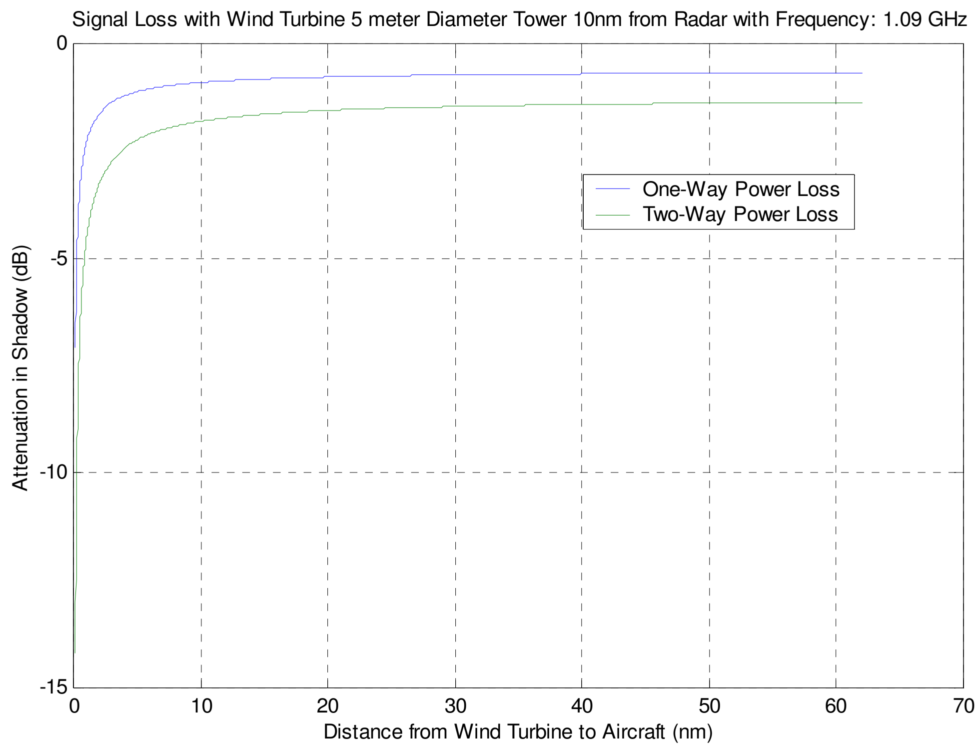


Figure 15

Figure 15 shows a plot of 1-way and round-trip attenuation within the shadow at the frequency of ATCBI interrogations and replies. For replies and interrogations, only 1-way loss applies. At 20nm, the 1-way loss for transponder replies is about 0.8dB; much less than the 1-way, or round-trip, attenuation anticipated for the search frequency. At the lower ATCBI frequencies, the Fresnel zone is much larger. Therefore, a smaller proportion of the direct signal is scattered by a wind turbine. The down side to this is that there are more geometries where more than 1 wind turbine might block the Fresnel zone between the radar and an aircraft.

Received Signal in Interrogator Receiver

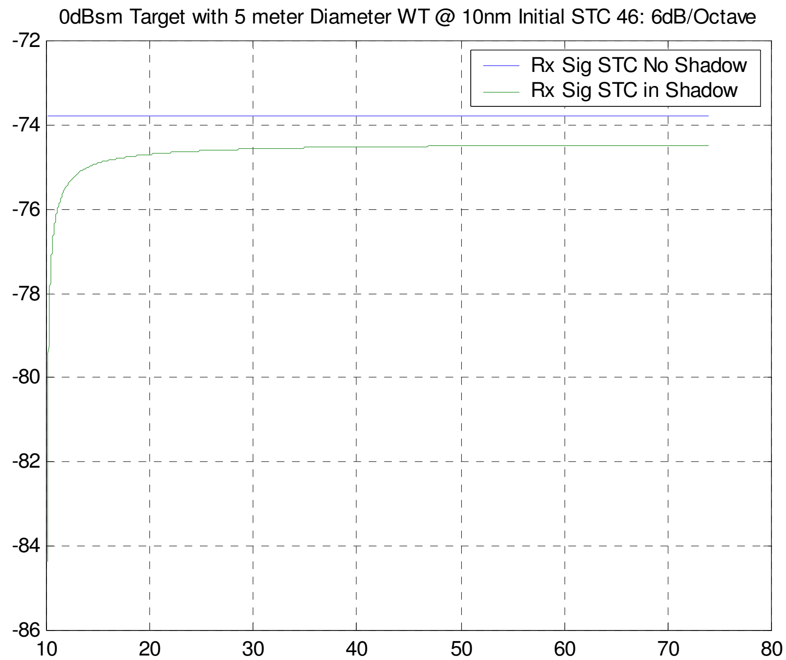
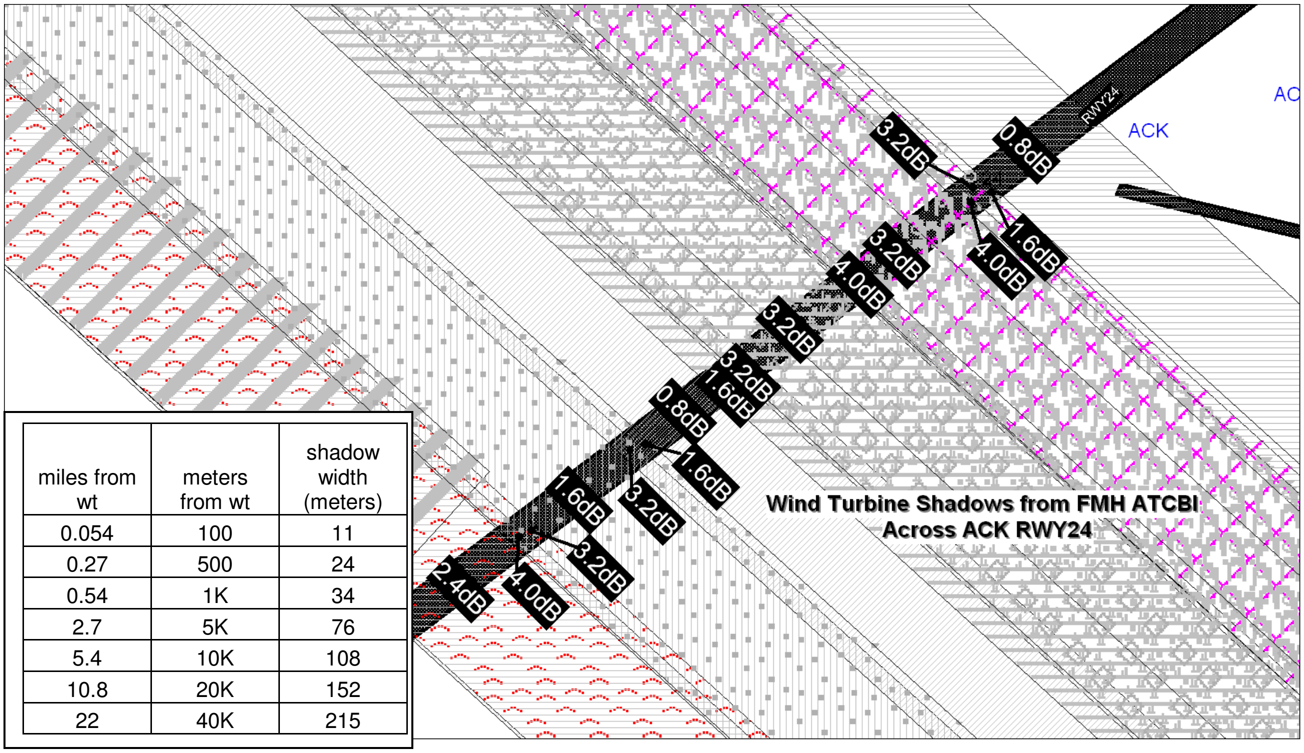


Figure 16

Figure 16 shows the expected magnitude of replies in the interrogator receiver. The conservative link budget calculation for this plot involved the minimum allowable transponder power, 2.5dB loss between the transponder and the fuselage antenna and 0dB gain attributed to the aircraft dipole antenna. The initial value for the 20dB/decade STC at the interrogator was 46dB at 1nm. The MDS for a beacon interrogator is -82dBm; 7dB below the signal levels calculated in this link budget. Even when considering worst case shadowing with a conservative link budget, there is still a margin of 7dB before the replies approach the MDS level of the beacon.

Shadows Beacon on ACK Runway from Wind Turbines Illuminated by FMH



miles from wt	meters from wt	shadow width (meters)
0.054	100	11
0.27	500	24
0.54	1K	34
2.7	5K	76
5.4	10K	108
10.8	20K	152
22	40K	215

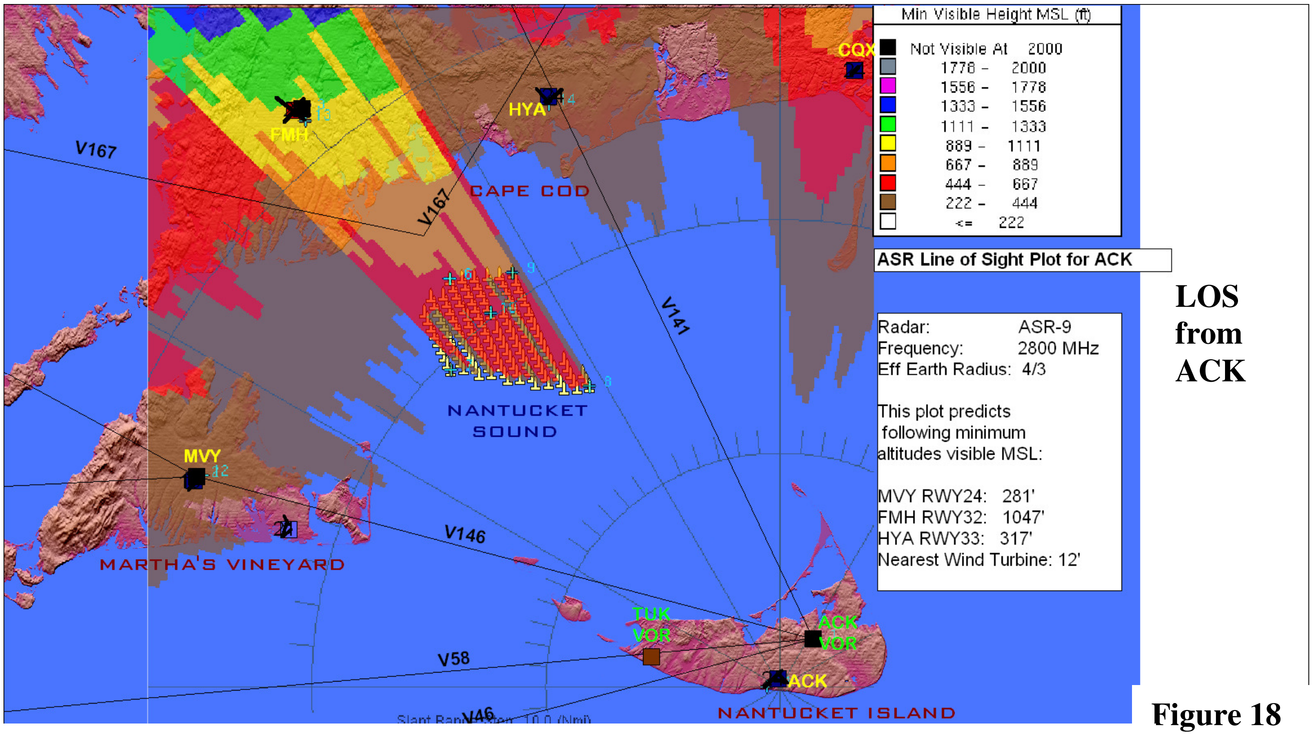
Figure 17

Figure 17 depicts the shadows from 14 wind turbines illuminated by the FMH ATCBI falling across ACK runway 24. The beam width of the beacon antenna is about 2.3° as opposed to the search beam which is 1.4°. Because of the lower frequency, each shadow is also about twice the width of a shadow from search radar illumination. The effective attenuation in each shadow for the transponder replies is much lower than the attenuation to search echoes. **Figure 17** shows labels of cumulative attenuation to transponder replies and ATCBI interrogations across ACK runway 24. The width of a shadow at various ranges from an illuminated wind turbine is shown in the lower left of **Figure 17**. As in **Figure 17**, the values of attenuation shown are based on shadows that are uniform across their width.

Vertical extent of shadows from wind turbines

Finally, the vertical component of the shadows must be considered. To get an idea of the vertical extent of the shadows, the wind farm was modeled as a single giant metal building in RSS. Then line of sight plots were generated for the ASR frequency with the obstruction added to the cultural data-base.

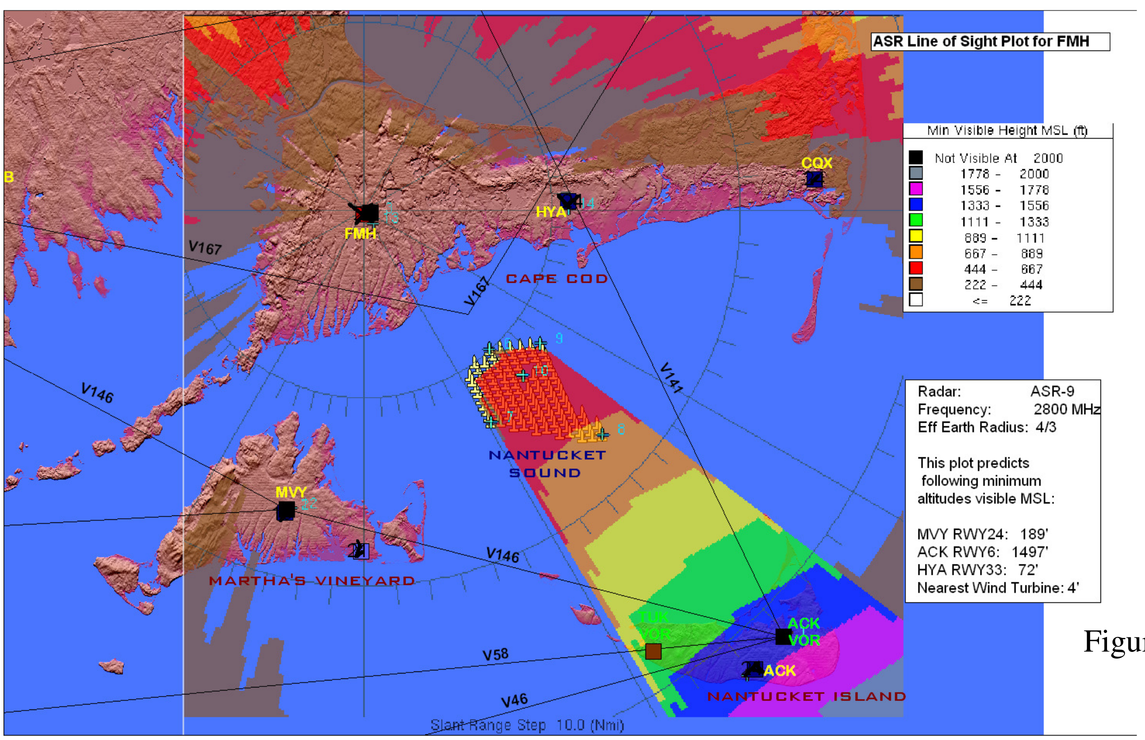
Vertical extent of shadows from wind turbines Using RSS LOS Plot



LOS from ACK

Figure 18

Figure 18 shows that the wind farm will impact coverage over Falmouth from ACK. The LOS plot predicts that the shadows from the wind farm illuminated by ACK will extend to 1050'MSL over Otis Airfield



LOS from FMH

Figure 19

Figure 19 shows that the wind farm will impact coverage over ACK from FMH. The LOS plot predicts that shadows from the wind farm illuminated by FMH ASR-8 will extend to 1500' MSL over Nantucket.

Clutter

When the wind blows across Nantucket Sound from the Northwest or the Southeast, the motion of the wind turbine blades will be mostly tangential with respect to the radars at FMH and ACK. The clutter and resulting effects during such conditions would be minimal and unlikely to impact air traffic operations. However, when the winds are from the northeast or the southwest, the motion of the blades will be mostly radial. The result will be many large amplitude, Doppler shifted returns resulting in moving clutter.

ASR-8, Clutter and Mitigation

In terms of processing, the ASR-8 is very susceptible to wind turbine clutter. In addition, the ARTS automation system fed by the ASR-8 has no means of filtering analog video from the ASR-8, but rather displays any video output from the ASR-8. As a result, much clutter will be displayed on the controller's screens when the wind is blowing Excessive clutter can be a distraction to air traffic controllers, and excessive clutter makes the task of tracking aircraft without transponders across the wind farm difficult. The echoes from the blades will also obscure the echoes of aircraft that fly directly over them. It is also likely that the wind turbine clutter will lower the PD in the vicinity of the wind farm. Not only will the PD be low over each wind turbine, but the ASR-8 also employs a mean filter CFAR, which will cause the detection thresholds for range cells adjacent to a wind turbine to be raised due to the wind turbine clutter. To determine the detection threshold for a particular range cell during 1 PRT, the ASR-8 CFAR averages the echoes from adjacent range cells at the same azimuth for 1/2 nmi on either side of the range cell of interest.

CFAR Operation

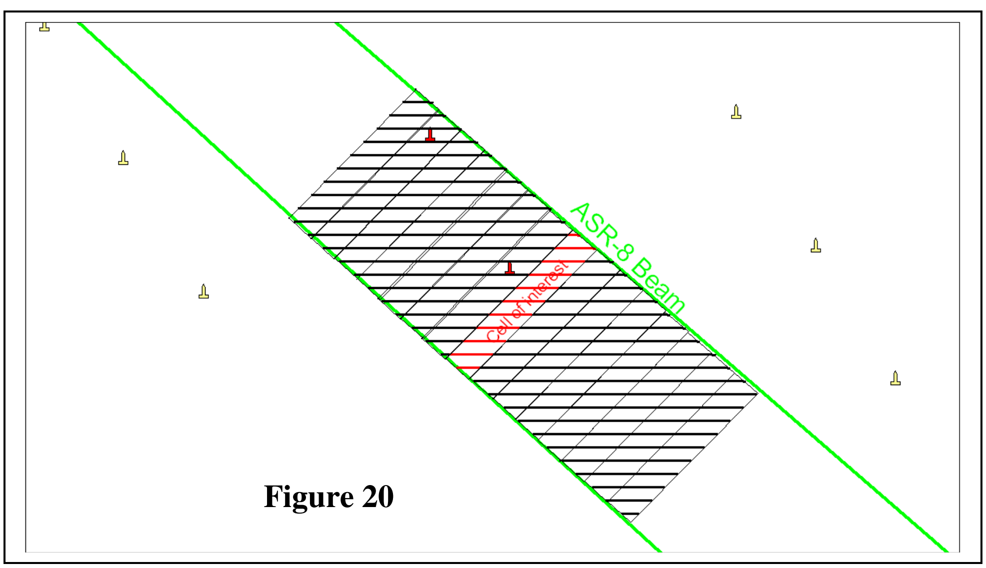


Figure 20

7* 1/16nm wide range cells on either side of the cell of interest are used in the CFAR calculation. The radar will typically see groups of 2 or 3 wind turbines .3nm apart with 1nm between each group. This will result in the threshold being raised over most of the wind farm when the wind is blowing in a direction that would result in clutter.

Where the ASR-8 is concerned, there are very few means of mitigating the clutter. The ASR-8 receives on two beams which are separated vertically by about 3.5°. Transmission occurs on the low beam only; usually aimed 2° above the horizon. The high beam is used during receive time for the first 12 – 15nm to mitigate ground clutter. For a given range, the ASR-8 can process only one beam: high or low. The transition point to switch from high beam to low beam is site configurable via jumpers which are set during optimization of the radar. The farthest wind turbine from FMH is just over 16nm, so the high beam/low beam transition point for FMH could easily be moved to a radius beyond the wind farm. A 3.5° offset of the vertical beam is equivalent to 15-20dB of attenuation from the nose of the beam. There is evidence to suggest that the side profile of the wind turbine blades may have a radar cross section (RCS) greater than 20dB. If the blades do have a RCS greater than 20dB, then using high beam over the wind farm will knock the clutter down quite a bit, but it is not likely to eradicate the clutter completely.

TDX-2000

The only other means of mitigation for the ASR-8 is to equip the site with a digitizer/post processor such as the Sensis TDX-2000. TDX-2000s have been installed all over the country, and are known to perform well with the ASR-8. The TDX-2000 is supported by the FAA, and the National Tech Ops Automation Group in Atlantic City, NJ could be tasked with optimizing a TDX-2000 at FMH. TDX-2000 has many post processing tools and features that are designed for operating in a high clutter environment. Among the TDX-2000 features are a search tracker, beacon tracker, beacon code degarbling, merging of beacon and search, clutter maps, multiple PRT storage, multiple scan storage and run-length discrimination. Though the performance of the TDX-2000 has not been tested next to a wind farm, there is no doubt that the TDX-2000 would greatly enhance the radar product from the ASR-8.

The output of the TDX-2000 is digital target messages. This would allow the FMH ARTS-2E to be modified to accept digital target messages. There are many advantages to an ARTS configured to accept data instead of video.

1. The ARTS-2E has a search tracker that can be programmed to not drop tracks over a certain area; a wind farm, for example. If the radar missed a primary only target over the wind farm enough times to drop the target from the TDX-2000 track list, the worst case result is would be that the tracker would not re-acquire the target for up to 20 sec after clearing the wind farm. The first time the radar misses the target, the ARTS-2E will display a coast symbol at the aircraft's predicted position. If the ARTS-2E is programmed to not drop tracks over the wind farm, the coast symbol will display until the predicted position is beyond the wind farm. This will provide an approximate position for the aircraft as well as notifying the controller that the aircraft has lost radar contact.
2. The ARTS-2E displays could be upgraded from analog to digital.
3. There are upgrades to the ARTS-2E, available or in development, that require a digitized radar input and digital displays. An upgrade in development is the ability to switch between up to five radar inputs.

ASR-9, Clutter and Mitigation

As discussed previously, the ASR-9 is has a much greater capacity to deal with moving clutter than the ASR-8. Like the ASR-8, the ASR-9 receives on one of two beams, with the transition point set to around 15 nmi. The difference between the high beam and the low beam should be 15 – 20 dB. In addition to the high beam/low beam transition, the ASR-9 also has post processing functions such as a tracker and the adaptive geocensor. The adaptive geocensor of the ASR-9 PAC-II has a final resolution of 1.4° X 1/16 nmi. However, this fine resolution takes hours to achieve, and even sustained winds are dynamic over a period of minutes. During sustained winds where the blades have a high degree of radial motion toward the radar, it has been observed that the dynamic geocensor function of the ASR-9 will raise the detection thresholds over the wind farm high enough to decrease the probability of detection over the wind farm by as much as 10 - 20%. The decrease in PD will manifest as a lower search reinforcement rate over the wind farm and dropped search only targets i.e. aircraft without transponders.

Air Traffic controllers will see much less clutter from the ASR-9. There will be a decrease in search PD by 10 – 20%., most likely closer to 10%. over the wind farm due to the wind turbines directly, and to detection thresholds being raised as a result of the geocensor function of 9PAC-II.

The following is a discussion of the performance of 9PAC-II at Palm Springs, CA. Search PD over the wind farm at Palm Springs is reduced by 20%, but there are important differences between the wind farm at Palm Springs and the proposed wind farm in Nantucket Sound. The Palm Springs discussion ends with a brief examination of theses differences.

9PAC-II Performance at Palm Springs, CA

A good place to study the performance of 9PAC-II is Palm Springs, CA.

Figure 21

Palm Springs, CA has 2,200 wind turbines within 10nm of the ASR-9 for Palm Springs Intl Airport: rows, ¼ mile apart, of wind turbines 250 feet apart along each row. The Palm Springs ASR-9 was a test and development site for the 9PAC-II geocensor.

Palm Springs, CA, where 2,200 closely spaced wind turbines within 10 nmi of an ASR-9, made the location a great test bed for the 9PAC-II geocensor. The densest part of the wind farm is on the main approach path to Palm Springs Intl Airport (PSP). **Figure 22** shows 3 different presentations of a 2 ½ hour file played back in WinPlot (Appendix A - WinPlot) and filtered by range and azimuth to show only traffic over the densest part of the wind farm. During this 2-hour recording, 61 aircraft with transponders flew over the wind farm. The recording was made 11/27/08. The grey box at the far left of **Figure 22** shows the statistics only over the wind farm for the recording. It shows that beacon reinforcement rate was 79% over the wind farm. Beacon reinforcement for the whole site during the 2-hour recording was 91.6%. Beacon PD over the wind farm, according to the statistics, was 99.26%. A search-reinforced-beacon message results when both the search radar and the beacon report the same target at the same position during the same antenna scan. A beacon-only message results when *only* the beacon reports a target at a particular position during one antenna scan. A beacon-only message implies that the search radar missed the target during that particular scan. The beacon, especially the Mode S Beacon Interrogator, is much more reliable than the search radar with PD normally around 100%. Therefore, search reinforcement rate is a good approximation of search PD. This file shows that the ASR-9 had an approximate PD of 79% over the wind farm during those 2.5 hours.

Statistics Over Wind Farm at PSP

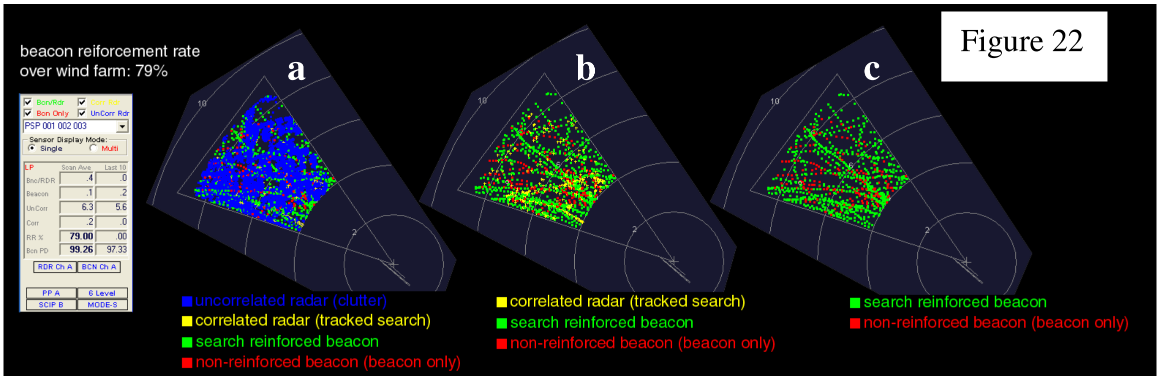


Figure 22a is covered with blue uncorrelated radar blips (from ASR-9 digital target messages). The blue field of uncorrelated radar is a good indication that the wind was blowing that day. **Figure 22b** shows the sum total of what the air traffic controllers saw over the course of the 2.5 hours. Most of the yellow correlated blips are also due to wind turbine clutter that met the requirements of the tracker. **Figure 22b** shows that there is still some clutter breakthrough from the ASR-9 post processor, but F**igure 22a** gives an understanding of how much clutter is not displayed at the controllers' consoles. **Figure 22c** displays only the reinforced and non-reinforced beacon blips; 900 messages total: 189 non-reinforced, 711 reinforced. 711/900=.79 .79 was just for 1 two-hour recording. Analysis of 170 hours of recordings from PSP ASR-9 from November and December 2008 revealed an overall average reinforcement rate of 73.7%.

After an optimization of the PSP ASR-9, the ASR-9 National Operations Support Group conducted a flight check over the wind farm using a Cessna 172. The flight check report showed over 80% search PD. **Table 1** gives the results of radar reinforcement over the wind farm from 170 hours of data recorded during the months of November and December 2008. Considering the density of the wind turbines at PSP, 73.7% is much better than without the 9PAC-II

Table 2

	170 hours of PSP ASR-9 data
92.69	Average RR over coverage volume
73.73	Average RR over wind farm

Comparison of Palm Springs and Nantucket

There are some important differences between the wind farm at Palm Springs and the proposed wind farm in Nantucket Sound.

1. The wind direction and resulting orientation of the wind turbines at Palm Springs is consistent. The wind farm at Palm Springs is located on the floor of a valley at the mouth of what resembles a venturi between two large mountains. Therefore, the wind blows consistently along one particular axis. The resulting aspect angle that the radar has to most of the rotating blades produces echoes with sufficient amplitude and Doppler content to be classified as moving targets. Nantucket Sound is fairly open water along the coast, and the wind can change directions over the course of a single day. This means that even if the wind is blowing, the direction of the wind could, at times, favor radar coverage over the wind farm. This situation should definitely result in higher average PD compared to the PD observed over the Palm Springs wind farm.
2. The density of the wind farm at Palm Springs is much higher than the proposed wind farm in Nantucket Sound. Within the rows of the wind turbines, there is only 250' of separation between individual towers. The width of the ASR beam is about 600' in the center of the wind farm at Palm Springs. A range increment for the ASR-9 is 1/16 nmi or 380'. This means that each range, azimuth bin over a row of wind turbines contains more than one wind turbine. Therefore, the detection thresholds remain very high for the full length of each row of wind turbines when the wind is blowing. In Nantucket Sound, the propose layout of the wind farm is on a grid that provides ¼ mile separation between wind turbines North to South, and 1/3 mile separation East to West. This will allow the detection thresholds in the spaces between the wind turbines to remain lower than the thresholds directly over the wind turbines. The proposed arrangement of the Nantucket wind farm should definitely result in a higher PD compared to the PD observed over the Palm Springs wind farm.
3. The wind farm at Palm Springs is on the main approach path to Palm Springs Intl Airport. This means that many aircraft departing from or arriving to Palm Springs Intl Airport must be vectored over the wind farm. The proposed wind farm in Nantucket Sound is out of the way of major traffic patterns, and aircraft do not have to be vectored over the proposed location. Aircraft without transponders will have no requirement to fly over the wind farm. The wind farm at Palm Springs might see as many over flights in one hour of an average day as the proposed wind farm in Nantucket Sound might see in one whole day of busiest weekend of summer. This means that the Nantucket wind farm is far less likely to impact radar coverage and operations compared to the Palm Springs wind farm.

Considering these three factors, it is reasonable to predict that the ACK ASR-9 will generally have higher PD over the proposed Nantucket wind farm than the PSP ASR-9 has over the Palm Springs wind farm.

Figure 23

Figure 23 gives an idea of the density of the wind farm at Palm Springs, CA

Track Seduction

Since echoes from wind turbine blades could meet target detection requirements of the AR-9 processor, it is possible for the ASR-9 tracker to update the positions of tracked aircraft with wind turbine clutter. This would most likely occur if an aircraft without a transponder were obscured by wind turbine clutter, or was missed due to excessive detection thresholds. In this case, it would be possible for the tracker to get off course and track wind turbine clutter in a direction away from the path of the actual aircraft. Were this to occur, the real aircraft would be dropped from the track list and could not be displayed again until being detected for 3 out of 4 consecutive scans. Since the ASR-9 tracker will not initiate a track in a range, azimuth bin where clutter counts are high, the aircraft might not reacquire until after passing over the boundary of the wind farm. In the mean time, the tracker could continue to track wind turbine clutter across the entire wind farm. The distances between the wind turbines in the proposed Nantucket wind farm is conducive to maintaining sufficient sensitivity between the turbines as to allow detection between the wind turbines. Also, setting the high beam / low beam transition point beyond the range of the wind farm for high/low beam will reduce wind turbine clutter by 15 to 20dB. These two factors could help increase search PD over the wind farm and decrease the likelihood of track seduction. According to FAA staff at Palm Springs and National Ops Support, track seduction hasn't been noted as a problem, and no incidents of the phenomenon were observed in the data collected for this report.

Traffic Patterns over the proposed Nantucket wind Farm:
In order to predict how the wind farm may impact coverage of the area and air traffic operations, it is important to have an understanding of the traffic patterns in the area of the wind farm. During the summer months, Nantucket sound has some of the highest air traffic volumes in the country, especially when it comes to small aircraft. During the summer, Nantucket Airport may see 1000 aircraft / day [4]. To gain perspective of the traffic patterns of the area during peak traffic days, the following ACK data recordings were downloaded from the Boston ARTCC ERIT server for the following dates and local times:

Table 3	Date	Time		Number of aircraft that overflew wind farm		
		Zulu time	Local Time	Aircraft without transponders	Aircraft with transponders	
2008 4th of July Weekend	4-Jul	1645-2200	1245-1800	4	30	
	5-Jul	1700-2200	1300-1800	1	10	
	6-Jul	1500-2000	900-1600	4	23	
Labor Day Weekend 2008	29-Aug	1645-2145	1245-1745	2	21	
	30-Aug	1645-2245	1245-1845	0	17	percentage of aircraft without transponders
	31-Aug	1400-1600	1000-1200	0	19	
	1-Sep	1900-2400	1500-2000	7	47	
			Totals	18	167	10%

Table 4			Aircraft without transponders	Aircraft with transponders	Percentage of aircraft without Transponders
10/7/2007	20 hours		3 at most	13	
10/10/2007	24 hours		3 at most	15	18%

Previously, 44 hours of ASR-9 format ACK data was analyzed. The results are shown in Table 4 at left

Methodology for Viewing Traffic Over Nantucket

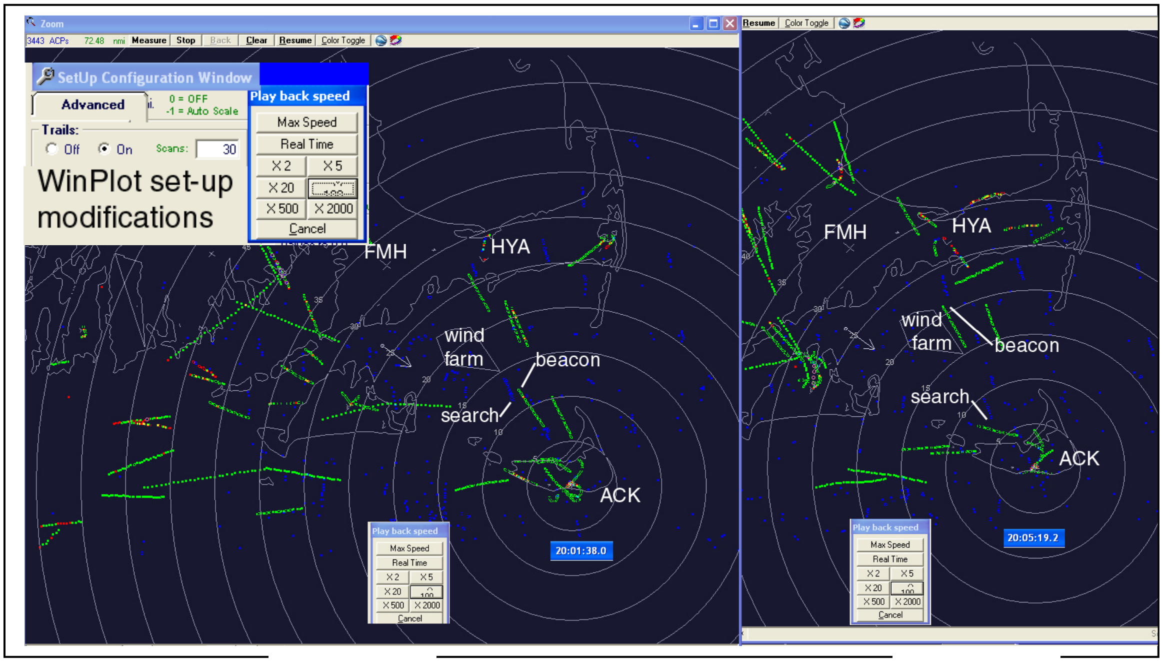


Figure 24a **Figure 24b**

The aircraft counts were derived in the following manner:

1. The files were downloaded from the Boston ERIT. Each file was 15 min in duration and contained data from multiple sites.
2. The files were filtered for ACK and then concatenated by date using RADES System 3, analysis software provided by USAF Radar Evaluation Team.
3. The concatenated, filtered files were viewed in WinPlot with the following settings:
   a. speed = real time *100
   b. trails on with 30scans selected
4. Aircraft were counted during file playback
5. A background map including an outline of the wind farm was loaded into WinPlot

Figure 24 demonstrates the set-up that was used to count the traffic that overflew the wind farm for certain hours and days during July 4th Weekend and Labor Day Weekend 2008. **Figure 24 a,b** are screen-shots from a program that replays radar data files. **Figure 24b** is approximately 4 sec later than **Figure 24a**. The two figure show a reinforced beacon and a search only target as their paths cross just south of the proposed wind farm.

The limitation of viewing ERIT data to make the count is that the data format of the files is CD-2 format as opposed to ASR-9 format. ASR-9 format reserves a bit in one of the search message words to declare whether the target is correlated or uncorrelated. WinPlot allows the option to view correlated messages only. This includes only search targets that meet minimum speed requirements and correlate to a track. Using ASR-9

Format data with correlated messages would have decreased the level of effort required to make the count while increasing the level of confidence that the count is accurate.

The proposed wind farm is not located along any airways, nor is it located beneath any approaches to any of the nearby airports. From an examination of the data downloaded from the fourth-of-July weekend and Labor Day weekend, there doesn't appear to be excessive amounts of traffic flying over the proposed wind farm. A total of 36 hours was analyzed. From the 36 hours that were examined, 185 flights over the proposed wind farm were counted: an average of 5 aircraft each hour. Of the 185 flights, just under 10% were without transponders: an average of 1 every 2 hours. Previous examination of 44 hours of ACK ASR-9 format data from 10/07/2007 and 10/10/2007 revealed that 2 aircraft without transponders flew over the proposed area, and 4 others flew very close to the wind farm. During the recordings from 2007, 28 aircraft with transponders flew over the wind farm.

Elevation Plot of Traffic Over Proposed Wind Farm

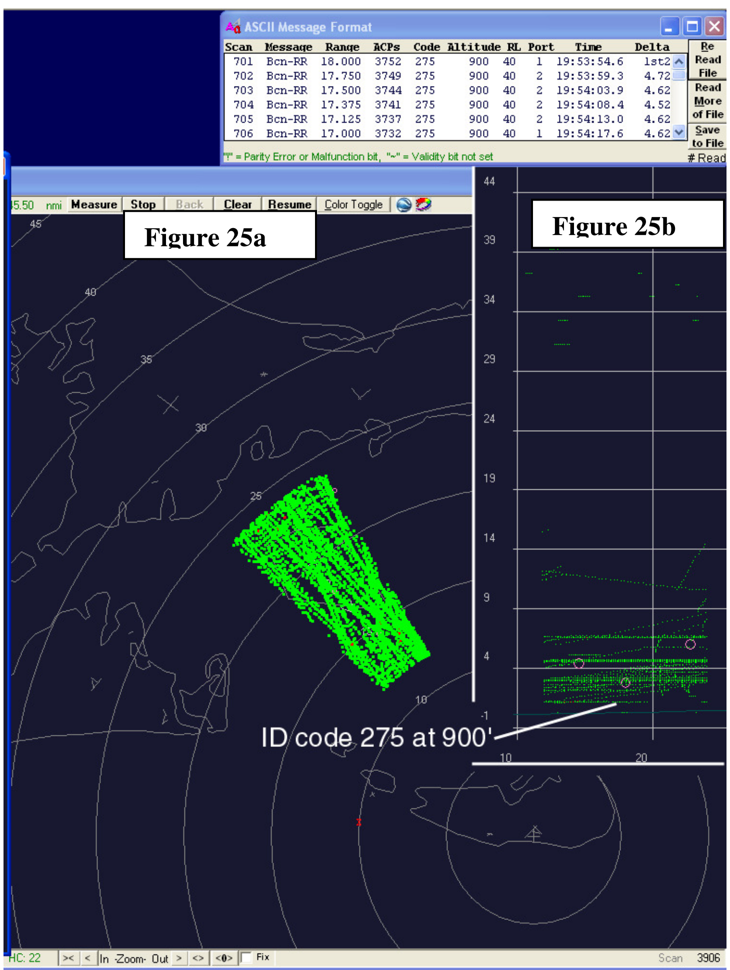


Figure 25

Figure 25 shows all the transponder traffic that overflew the proposed wind farm during the hours collected for Sep 01, 2008. **Figure 25a** is an range, azimuth plot. **Figure 25b** is an elevation plot that shows the same traffic on a range versus altitude plot. Note that the lowest flight over the proposed wind farm of an aircraft with a transponder was Mode 3 ID 275 at an altitude of 900'. The altitudes of the aircraft without transponders are unknown. This shows that traffic flying over the area generally flies well above the height of the wind turbines.

Conclusions - Impacts of Nantucket Wind Farm

Beacon Impacts

Based on the evidence presented in this report, it appears unlikely that the wind turbines will have any noticeable impact on the beacon performance. It is not possible, at this point, to completely rule out the potential for signal reduction and multipath propagation behind the wind turbines causing beacon misses, especially low in the beam. Fading will result in beacon misses below 600' within 2 nmi behind the wind farm. Traffic patterns for the area suggest that aircraft do not fly below 600' in the vicinity of the proposed wind farm. This fading could occasionally result in missed replies below 1,000' over Nantucket for the FMH ATCBI-5 and below 1,000' over Otis for ACK Mode S. Mathematical models and empirical evidence suggest that such occurrences will be infrequent and will not impact air traffic operations. If it were to have an impact, it would only be when ACK Mode S or FMH ATCBI-5 is out of service. There is also no evidence to suggest that the wind farm will cause false targets from reflections or beam distortion. It is unlikely that there will be a noticeable change to secondary coverage for FMH, ACK or QEA beacon systems

FMH ATCBI-5	No noticeable impact
ACK Mode S	No noticeable impact
QEA ATCBI-6	No noticeable impact

Search Impacts

Shadowing Effects

Given empirical evidence and a conservative treatment of shadowing equations, primary radar signal reduction from fading resulting in missed targets behind the wind farm is unlikely to impact air traffic operations, though it can not be ruled out completely. Fading, due to wind turbine shadows, will result in primary misses below 600' within 3 nmi behind the wind farm. Traffic patterns indicate that pilots do not fly below 600' in the vicinity of the proposed wind farm. There is a marginal possibility that fading behind the wind farm could result in some primary misses below 1,000' over Nantucket for FMH ASR-8, as well as below 1,000 over Otis for ACK-ASR-9. This could impact air traffic operations if FMH ASR-8 were required to provide primary service over Nantucket, or if ACK ASR-9 were required to provide coverage over Otis. Otherwise there should be no impact since ACK ASR-9 has a clear view south of the wind farm and FMH has a clear view north of the wind farm.

Mathematical models suggest that reduction of maximum range behind the wind farm is possible for FMH and ACK at lower elevations where the wind farm would provide some screening. This is especially true for the primary radars. This problem is mitigated by the fact that each radar provides better coverage in the volume that is degraded for the other radar. For example, in the area where there might be a decrease of maximum range for the ASR-8, the ASR-9 is 32 nmi closer and provides much better coverage. In addition, data from ACK indicates that there is not very much traffic 25 nmi Southwest of Nantucket Island.

Clutter Effects

FMH

When the wind is blowing from the Northeast or Southwest, clutter from the ASR-8 will be excessive in the vicinity of the wind farm. ASR-8 detection is not likely to change dramatically over the wind farm except directly over a wind turbine. The clutter will significantly reduce the controllers' ability to track primary only targets (aircraft without transponders) over the wind farm. It is likely that the level of clutter presented by the ASR-8 will be intolerable.

ACK

When the wind is blowing form the Northeast or the Southwest, the Probability of Detection (PD) over the wind farm will decrease as a result of aircraft obscuration by wind turbine clutter. PD will be further lowered over the wind farm due to the ASR-9 adaptive geocensor raising detection thresholds across the wind farm. The overall reduction in PD over the wind farm could be as much 20% but is more likely to be closer to 10% and will be noticed by air traffic controllers in the following ways.

- Decrease in the beacon reinforcement rate over the wind farm
- Misses of primary only aircraft

There will also be minimal amount of wind turbine clutter displayed on the controllers' screens. However, the general consensus from other air traffic control facilities where an ASR-9 is operating with 9PAC-II close to a wind farm is that the level of wind turbine clutter apparent to air traffic controllers is acceptable.

Track Seduction and Dropped Tracks

The ASR-9 tracker could be susceptible to track seduction which could result in dropped tracks over the wind farm. The default setting for an ASR-9 to drop a track is 4 misses in a row. A dropped track can be reacquired and displayed as a correlated target after 3 out of 4 hits. This type of track seduction is a rare occurrence and is possible only for aircraft without transponders. ACK data suggests that very few aircraft without transponders fly over the proposed wind farm. It is more likely to be the case that a tracked target could coast for 4 scans in a row without the occurrence of track seduction. When this occurs, the ARTS can be programmed to not drop tracks over the wind farm. Under these circumstances, the ARTS-2E could display a special coast symbol at the predicted position of the aircraft until the target was re-acquired by the search tracker.

Recommendations

The following are recommendations for the case that the wind farm is erected as proposed

1. A TDX-2000 should be installed for the ASR-8 at FMH and optimized by the TDX-2000 National Ops Support group.
   Estimated Cost: $1.5 Million

2. The ARTS-2E associated with the ASR-8 should be modified to accept a digital input.
   Estimated Cost: To be determined

3. The Displays at the Cape TRACON should be upgraded to digital displays.
   Estimated Cost: To be determined

4. Common ARTS does not allow a sensor mosaic, but there may be upgrades or alternatives to the current configuration to increase the flexibility of ARTS-2E. The Common ARTS Program Office and Common ARTS National Ops Support group should be consulted to determine if there are any upgrades or alternatives to the current configuration of the automation systems at the Cape TRACON. Any cost associated with these upgrades should be considered during negotiations with the wind power provider.

5. The high beam/low beam transition point should be place beyond the extent of the wind farm for each ASR.

6. Tech Ops should ensure that there are no performance problems with the ASR-8 or the ASR-9 prior to installation of any wind turbines.

7. Baseline recordings should be made for the ASR-8 and ASR-9 prior to the installation of any wind turbines. These recordings should be compared to recordings made after the wind turbines have been installed. These recordings should be made under different weather conditions during winter and summer. Data recordings with the ASR-8 can be made as soon as a TDX-2000 has been installed. In addition to data recordings, recordings with the Radar Analysis Support System (RASS) should be made. Any impacts from the wind turbines can be measured by a comparison of these recording

References

1. NTIA Technical Report TR-08-XXX, "Assessment of the Effects of Wind Turbines on Air Traffic Control Radars"; John J. Lemmon, John E. Carroll, Frank H. Sanders.

a. Section 3.4 p11

2. Eurocontrol Document, "Assessment Methodology to Determine the Impact of Wind Turbines on ATC Surveillance Systems", 5/18/2007

a. Section C.5 p73

3. Photo of wind turbine on truck, taken by Brad Moon and posted August 25, 2008 "Windmills: Coming to a Shoreline Near You" on Wired Blog Network.

4. Report for NPR, "Nantucket Air Traffic", by Kate Splaine, December, 2008