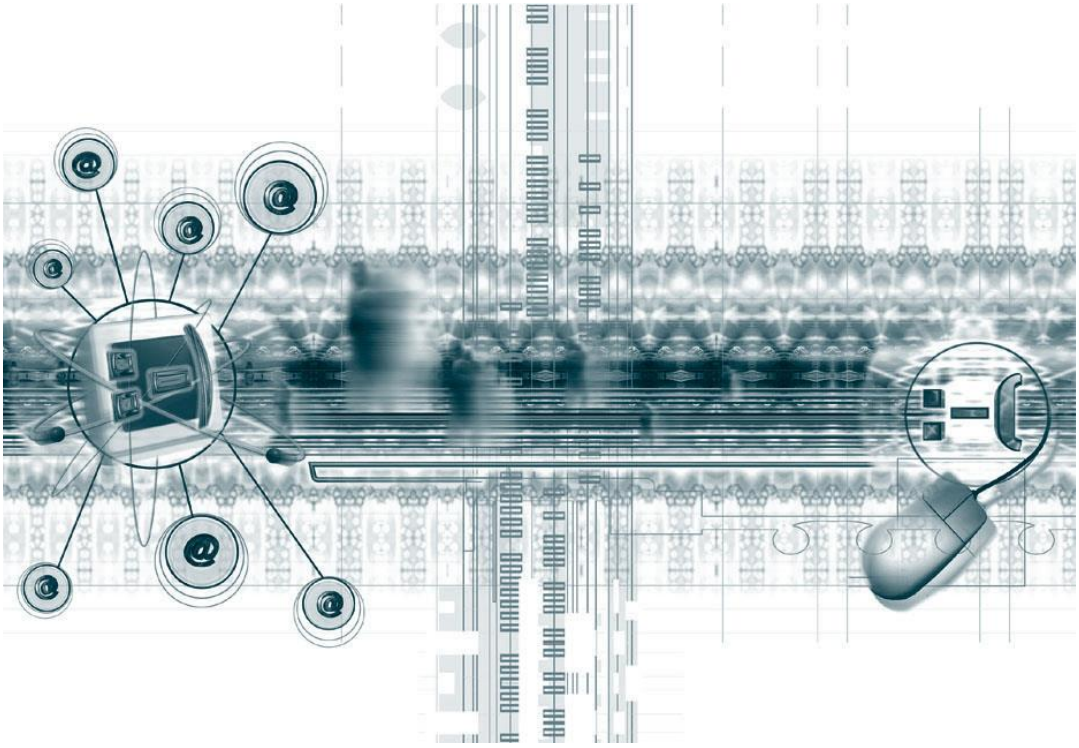
Algorithms
Radar, radio and wind turbines

Dr Eldar Aarholt



04.10.2015

Version 2

Contents

List of figures

List of tables

Algorithms
Radar, radio and wind turbines

1 Introduction

This document gives an overview of various electronic system parameters that may be subject to wind turbine interference.

1.1 Typical equipment

The following tables contain typical data for primary radar system, secondary radar system, radio links, broadcast systems and mobile communication systems.

Radar parameters PSR[1]	**Values**
Typical radar data	ASR-8
Radar frequency (*f*)	2.7-2.9 GHz
Wavelength (λ)	~0.1 m
Peak power $dBm = ((10xLog_{10}(Power\ Watt)) + 30)$	1 MW (+90 dBm)
Antenna gain (log / lin) Antenna gain = $\pi^2 * d^2 / \lambda^2 * k_{eff}$ $dBi = ((10xLog_{10}(antenna\ gain))$	40 dBi / 10000
Antenna beam width $_{(horizontal)}$ (*-3dB)*	1.7°
Antenna width (*d*)	4.5 m
Antenna centre height above ground	~15 m
Instrumented range	111 km (60 NM)
Pulse length	0.5-6.0 µs
Antenna centre (masl)	TBD

Table 1. Typical PSR radar data

Radar parameters SSR	**Values** [2]
Radar type	Cassidian MSSR 2000i
Radar frequency (*f*)	TX 1030 MHz / RX 1090 MHz
Wavelength (λ)	0.2913 m
Peak power $dBm = ((10xLog_{10}(Power\ Watt)) + 30)$	2000 W (+63 dBm)
Antenna manufacturer	Antenna Associates ca 4.2 m (14 ft)
Antenna gain (log / lin)	30 dBi / 1000
Antenna beam width $_{(horizontal)}$ *-3dB*	5.0°
Antenna centre height above ground	TBD
Instrumented range	278 km (150 NM)

Table 2. Typical SSR radar data

---

[1] Merill Skolnik, Introduction to Radar Systems, McGraw-Hill, page 204, 1981

[2] Eurocontrol Guidelines v1.2, Annex D3, page 61, 09.2014

Radio link component	Values
Antenna type	Parabolic
Antenna diameter	2 m
Radio link frequency (*f*)	4.5 GHz
Wavelength (λ)	0.067 m
Typical peak power *dBm = ((10xLog$_{10}$(Power Watt)) + 30)*	100 W (+50 dBm)
Antenna gain (log / lin)	37 dBi / 5000
Antenna beam width $_{(horizontal)}$ *-3dB*	2.4°
Antenna centre height above ground	TBD
Typical link distance	35 km

Table 3. Typical radio link parameters

Communications components	Values
FM radio frequency (*f*)	100 MHz
Typical peak power *dBm = ((10xLog$_{10}$(Power Watt)) + 30)*	10 kW (+70 dBm)
DAB radio frequency (*f*)	229 MHz
Typical peak power *dBm = ((10xLog$_{10}$(Power Watt)) + 30)*	2 kW (+63 dBm)
TETRA radio frequency (*f*)	390 MHz
Typical peak power *dBm = ((10xLog$_{10}$(Power Watt)) + 30)*	50 W (+47 dBm)
Digital TV frequency (*f*)	700 MHz
Typical peak power *dBm = ((10xLog$_{10}$(Power Watt)) + 30)*	50 kW (+77 dBm)
Mobile phone frequency (*f*)	900/1800 MHz
Typical peak power *dBm = ((10xLog$_{10}$(Power Watt)) + 30)*	20 W (+43 dBm)

Table 4. Typical radio communications system parameters

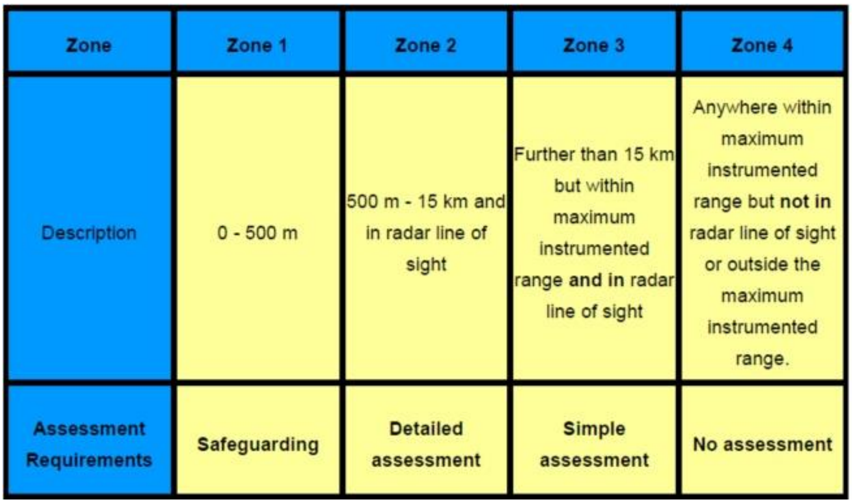
2 Eurocontrol’s recommendations

Eurocontrol give recommendations to Air Navigation Service Providers and to companies developing systems for wind energy of how to evaluate whether the wind turbines may affect the quality of surveillance services as well as to identify possible mitigating actions.

Eurocontrol’s recommendations apply to wind turbines with three blades, turbine heights from 30 m to 200 m and with a horizontal rotational axis.

2.1 PSR

Eurocontrol recommend[3] an exclusion zone of 500 m from primary radar, and for distances from 500 m to 15 km, a detailed assessment should be performed. For distances more than 15 km and within maximum instrumented range and line of sight, it is considered sufficient with a simple assessment containing the antenna position, frequency band and CFAR algorithm.



Zone	Zone 1	Zone 2	Zone 3	Zone 4
Description	0 - 500 m	500 m - 15 km and in radar line of sight	Further than 15 km but within maximum instrumented range **and in** radar line of sight	Anywhere within maximum instrumented range but **not in** radar line of sight or outside the maximum instrumented range.
Assessment Requirements	**Safeguarding**	**Detailed assessment**	**Simple assessment**	**No assessment**

Table 5. Eurocontrol’s recommendation for primary radar

2.2 SSR

Eurocontrol recommend[4] an exclusion zone of 500 m from secondary radar, and for distances from 500 m to 16 km within maximum instrumented range and in line of sight, a detailed assessment should be performed. For distances more than 16 km, no assessment is required.

Zone	Zone 1	Zone 2	Zone 4
Description	0 - 500 m	500 m - 16 km but within maximum instrumented range **and** in radar line of sight	Further than 16 km **or** not in radar line of sight
Assessment Requirements	**Safeguarding**	**Detailed assessment**	**No assessment**

Table 6. Eurocontrol’s recommendation for secondary surveillance radar

---

[3] Eurocontrol Guidelines v1.2, section 4.2.1, page 28, 09.2014

[4] Eurocontrol Guidelines v1.2, section 4.2.2, page 31, 09.2014

3 Methods and data

3.1 The electromagnetics of wind turbines

During the past few years, several international studies of electromagnetic interaction with radars, communication systems and wind turbines have been conducted. The following studies [5, 6, 7] illustrate relevant relationships of wind turbine tower radar cross section (RCS), signal shadowing and radar signal blockage.

With reference to the above studies, representative measured electromagnetic values for wind turbine considerations are as follows:

- If the tower side slant angle is 0.8º, the tower RCS becomes about 100 m^2, and it is reduced as a function of increasing slant angle (i.e. 10 m^2 at 2.7º slant angle). This is consistent with typical RCS values for large transport aircraft such as the Boeing 747.
- The turbine blades constitute a much weaker radar signal return than that of the tower (in the order of 30 dB weaker)
- Blockage and shadowing from a wind turbine is very small. The shadow from a wind turbine tower extends only a few hundred meters directly behind the tower with a width comparable to the tower diameter.

Hence, it can be safely concluded that radar system receivers and digitisation circuitry have sufficient dynamic range to handle the types of signal levels reflected from wind turbines.

3.2 Radar detection

There is no uncertainty about the fact that radars can detect wind turbines. The only way to be absolutely sure that radars will not be affected by a wind farm is to avoid direct electromagnetic line of sight between the radar and the wind farm. However, radars are made to detect different types of targets. Hence, detection of a wind farm is in general not considered to be limiting for radar detection capability.

A wind turbine is composed of three main parts that can be detected with varying signal strength. These are the tower, the nacelle mounted on top of the tower and the turbine blades.

UK Coast Guard has carried out experiments using land based marine radar systems. The results show clearly that vessels can easily be detected even when operating inside or behind a wind farm

3.3 Signal strength

When radars illuminate a wind turbine, the strongest reflections originate from the turbine tower. The signal can become very strong if the tower is at right angle to the radar line of sight (mirror reflection) and the distance between the radar and the tower is short. The strong reflected signal will mask reflected signals from other targets in close proximity to the tower.

---

[5] Qinetiq, Gavin J Poupart, Wind farm impact on radar aviation interests – final report, 2003, page 60, section 7.3.4.2 (radar cross section) and p B-12, section B.5 (shadowing)

[6] Qinetiq, Martin J Howard, Colin Brown, Results of electromagnetic investigations and assessments of marine radar, communications and positioning systems undertaken at the North Hoyle wind farm by Qinetiq and the Maritime and Coastguard Agency, Qinetiq/03/00297/1.1, MCA MNA 53/10/366, 22. November 2004 (radar cross section, shadowing, communication systems, navigation systems)

[7] Radar and Wind Farm Solutions, AMS, England, IEA London, 17-18 March 2005

However, the turbine tower mirror reflection condition is a very rare incident, because the tower slant angle of typically 0.6º - 0.8º gives rise to a much weaker reflected signal. Using the worst case calculated RCS is therefore considered to be too conservative when modelling expected reflected signal strengths from a wind turbine, which in turn would impose too stringent radar system requirements.

3.4 Range accuracy

As a rule of thumb, radar range accuracy is proportional to the inverse of the radar bandwidth, while the antenna beam width regulates the azimuth accuracy. Typical modern radar systems utilise Frequency Modulated (FM) long pulses with a relatively high bandwidth that provide high range accuracy across the radar instrumented range. A wind farm does not influence the radar range accuracy.

3.5 Range-Azimuth Gating (RAG)

One method to stop a signal from entering the radar receiver is to close the receiver for a certain range interval when the radar is looking at a known strong reflectivity target; such as a mountain range, a large industrial building, a busy road bridge, or a wind turbine. Many modern radar systems are equipped with such a functionality called “range-azimuth gating” or “RAG mapping”. The effect of using a RAG is that the radar will not receive or process signals from certain directions and range intervals.

Based on the radar type, signals up to a few hundred meters in front of and behind a range-gated interval will also be removed. However, the radar will operate as usual outside the range gate interval. In modern radar systems, the range gate can be implemented in software to remove a strong signal reflection from a known target.[8].

3.6 Shadowing

During the years 2007-2009, several experiments[9] were conducted to measure the radar shadow behind a wind turbine. The radar shadow is measured to be up to 2 dB reduced signal level a few hundred meters behind the wind turbine tower at a width comparable to the tower diameter. The radar shadowing is hardly measurable for longer distances.

Shadowing is considered to be much less of a problem than previously anticipated. In most reported cases, shadowing is a radar hardware and/or software induced effect; not an electromagnetic problem[10].

---

[8] Qinetiq, Gavin J Poupart, Wind farm impact on radar aviation interests – final report, page 60, section 7.3.4.2 (radar cross section) and page B-12, section B.5 (shadowing), 2003

[9] IEA topical expert meeting on radar, radio and wind turbines, Amsterdam 18-19 November 2009

[10] CAA policy and guidelines on wind turbines, CAP 764, section 2, page 3, 2012

3.7 Typical wind turbine data

A typical wind farm layout may consist of 10 to 50 or more wind turbines located about 300-400 m apart with heights varying from 100 m to 150 m.

Component	Turbine type
Tower	Conical tubes made of steel
Nacelle height	100 m
Rotor diameter	100 m
Maximum height about ground	150 m
Tower diameter at ground level	5.0 m
Tower diameter at nacelle	3.5 m
Tower slant angle	0.43°
Rotor revolutions	~6-18 rev/min

Table 7. Typical wind turbine data

3.8 Geometric considerations

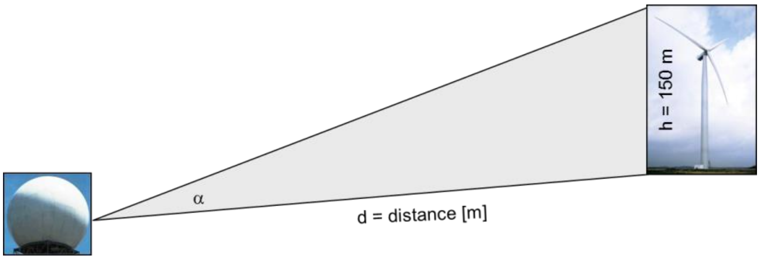


Figure 1. Elevation angle from radar antenna to the wind turbine

The wind turbine tower is the main contributor to a reflected radar signal. The elevation angle from the radar antenna to a wind turbine is calculated as follows:

$$\tan \alpha = h / D = (h_{vindturbin} - h_{antenne}) / D$$

- where α is the elevation angle from the radar antenna towards the wind turbine, $h_{antenna}$ and $h_{wind\ turbine}$ are their respective heights [masl], and D is the distance from the antenna to the wind turbine in metre.

If the distance from the radar antenna to the nearest wind turbine is 7.1 km, the antenna centre is at 64 masl and the wind turbine is located at 96 masl, the elevation angle from the radar towards the wind turbine becomes:

$$\tan \alpha = ((96) – (64)) \text{ m} / 7\,100 \text{ m} = +32 \text{ m} / 7\,100 \text{ m} = +4.5 \times 10^{-3}$$

$$\alpha = \tan^{-1} (+4.5 \times 10^{-3}) = +0.26º$$

The elevation angle from the radar antenna to ground level of the wind turbine becomes +0.26º (upwards).

The elevation angle towards the top of a 150 m tall wind turbine becomes:

$$\tan \alpha = ((96+150) – (64)) \text{ m} / 7\,100 \text{ m} = +182 \text{ m} / 7\,100 \text{ m} = +25.6 \times 10^{-3}$$

$$\alpha = \tan^{-1} (+25.6 \times 10^{-3}) = +1.47º$$

4 Radar coverage

4.1 Primary radar considerations (PSR)

It is easy to calculate the received reflected power P_{ref} from a wind turbine in the radar receiver using the radar equation:

$$P_{ref} = \frac{\sigma \cdot F^2 \cdot G_t \cdot P_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi)^3 \cdot D^4} \text{ W}$$

- where σ is monostatic radar cross section [m^2], F is the terrain loss between radar and wind turbine, G_t is the transmit antenna gain, P_t is the transmitted power [W], G_r is the receiver antenna gain, λ is the radar wavelength [m] and D is the distance between the radar and the wind turbine [m]
- Typical values are: σ = 500 m^2, F=1, $G_t = G_r$ = 40 dB = 10000, P_t = 1 000 000 W, λ = 0.1 m, D = 7100 m, π = 3.1416

With the above values, the reflected energy (P_{ref}) in the antenna equals -10 dBm, a signal power that is well inside any radar specifications. If the transmitted power is different from 1 MW (+90 dBm), or the radar cross section is different from 500 m^2, the received power in the antenna would vary accordingly.

4.2 Secondary radar considerations (SSR)

An air traffic transponder will answer the secondary surveillance radar signal if the received signal level is stronger than -71 dBm[11] (in the literature, somewhat different reference levels down to -77 dBm are used).

The reflected signal power from a wind turbine tower is a function of the radar transmitted power, the wind turbine radar cross section, the radar signal angle of incidence and the distance between the radar and the air transponder.

It is possible to calculate the received reflected power P_{ref} from a wind turbine received by the air transponder using the following equation[12]. Typical values are shown in brackets:

$$P_{ref} = \frac{\sigma \cdot F_{tw} \cdot F_{wr} \cdot G_{tw} \cdot P_t \cdot G_{rw} \cdot \lambda^2}{(4 \cdot \pi)^3 \cdot {D_{tw}}^2 \cdot {D_{wr}}^2} \text{ W}$$

- where σ is the wind turbine bistatic radar cross section [*100 m^2*], $F_{tw}=F_{wr}=1$ is the terrain loss, G_{tw} is the transmit antenna gain [*30 dBi = 1000*], P_t is the transmitted power [*2000 W*], G_{rw} is the receiver antenna gain [*0 dB = 1*], λ is the radar wavelength [*0.291 m*], D_{tw} is the distance between the radar and the wind turbine [*7100 m*], and D_{wr} is the smallest distance from the wind turbine to the transponder [*5250 m*]

Distance between a wind turbine and an air transponder shorter than 5250 m in relation to signal reflections is not relevant as documented by Eurocontrol[13].

---

[11] Sintef report, Analysis of possible consequences of collocating Avinor's Monopulse secondary surveillance radar and wind turbines, page 8, 16.04.2004

[12] Eurocontrol Guidelines v1.2, section D-2, page 58, 09.06.2014

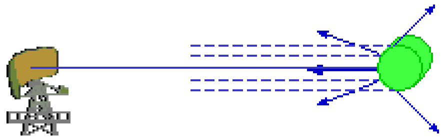
[13] Eurocontrol Guidelines v1.2, section D-3, page 61, 09.06.2014

Using the above values, the reflected power (P_{ref}) in the air transponder becomes -82.1 dBm, which is weaker than the signal of -77 dBm that would trigger a response from the air transponder.

4.3 Radar cross section

Radar cross section (RCS) is the measure of a target's ability to reflect radar signals in the direction of the radar receiver, i.e. it is a measure of the ratio of backscatter density in the direction of the radar (from the target) to the power density that is intercepted by the target.

Reflected signal from a cylinder: $\sigma_{max} = \frac{2 \cdot \pi \cdot r \cdot h^2}{\lambda}$



Maximum RCS (optical mirror reflection) for a cylindrical wind turbine tower of height 80 m, radius 2 m and radar frequency 3 GHz [λ=0.1 m] equals 804 248 m^2. However, due to the tapering of the tower as well as the non-coherent adding of radio wave reflections from the tower structure, the perceived RCS is usually several orders of magnitude less.

4.4 Antenna gain

The gain of a parabolic antenna (dbi) in a given direction is the amount of energy radiated in that direction compared to the energy an isotropic antenna would radiate in the same direction when driven with the same input power.

$$G_{dBi} = 10\ \log_{10}\left(\frac{\eta \cdot 4 \cdot \pi \cdot A}{\lambda^2}\right)$$

where η is efficiency [55 %], λ is wavelength [0.1 m] at 3 GHz, and A is physical aperture area [radius r = 1 m]. The isotropic antenna gain equals $10*\log_{10}(0.55*4*\pi*(\pi r^2)/\ \lambda^2)$ = 33.4 dBi.

5 Electromagnetic propagation algorithms

5.1 Near field distance

For a horn or dish antenna, the near-field distance can be taken as[14]:

$$D_{nf} = \frac{N_{nf}\eta D_a^2}{\lambda}$$

where N_{nf} is a constant, typically 1 or 2, setting the degree of conservatism, η the efficiency of the antenna (in the range 0.0 to 1.0), D_a is the diameter of antenna physical aperture, and λ is the wavelength.

The limit for near field considerations, when N_{nf} equals 2 and η equals 1 at λ = 0.067 m [4.5 GHz] and 2 m diameter antenna, is 120 m. Using a 3 m diameter antenna, the near field limit becomes 270 m. Hence, a wind turbine will usually be located in the antenna far field.

---

[14] D F Bacon, Fixed-link wind turbine exclusion zone method, section 1.3, page 4, 2002

5.2 Fresnel zone distance

Diffraction effects will be insignificant if obstructions are kept outside a volumes of revolution around a radio path know as a Fresnel zone. The extent of the Fresnel zone is calculated using the following equation:

$$F_n = \sqrt{\frac{n\,\lambda\,d_1\,d_2}{d_1 + d_2}}$$

where F_n is the n^{th} Fresnel zone radius [m], d_1 is the distance from antenna$_1$ to the wind turbine [m], d_2 is the distance from the wind turbine to antenna$_2$ [m], and λ is the wave length of the radio signal [m]. As can be seen from the equation, the extent of the Fresnel zone is a function of wavelength and distances. A distance of more than one Fresnel zone is considered safe distance. Often 1.5 or 2 Fresnel zones are used to allow for some margin in the calculations.

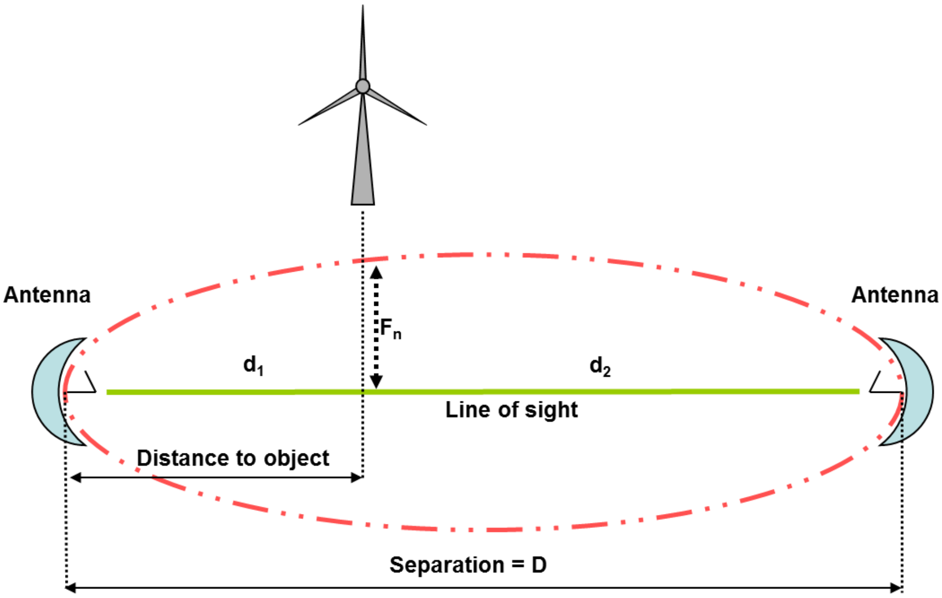


Figure 2. Illustration of the Fresnel zone around a radio path

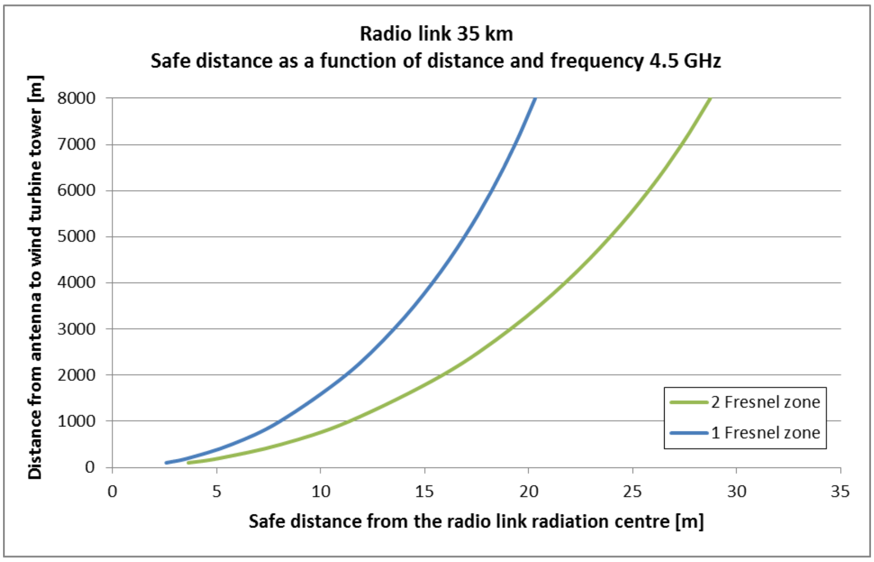


Figure 3. Safe distance from a typical 4.5 GHz radio link

5.3 Broadcast path loss algorithm

In telecommunication, free-space path loss (FSPL) is the loss in signal strength of an electromagnetic wave that would result from a line-of-sight path through free space (usually air), with no obstacles nearby to cause reflection or diffraction.

$$FSPL = \left(\frac{4\pi \cdot d}{\lambda}\right)^2 = \left(\frac{4\pi \cdot d \cdot f}{c}\right)^2$$

$$FSPL(dB) = 10 \cdot \log_{10}\left(\left(\frac{4\pi}{c} \cdot d \cdot f\right)^2\right)$$

where c is speed of light [$3e^8$ m/s], d is distance from the transmitter [f.ex 16 000 m], f is frequency [f.ex $700e^6$ Hz] and λ is the radio frequency wavelength [m]. The isotropic path loss equals -113.4 dBi using the above values.

References

D F Bacon, Fixed-link wind turbine exclusion zone method, version 1.1, released 28.10.2002

Eurocontrol, Guidelines on how to assess the potential impact of wind turbines on surveillance sensors, Doc.ID. EUROCONTROL-GUID-130, Edition 1.2, 09.2014

International Energy Agency Workshop, IEA Topical Expert Meeting on Radar, Radio, Radio Links and Wind Turbines", London, 17.-18. March 2005

International Energy Agency Workshop, IEA Topical Expert Meeting on Radar, Radio and Wind Turbines", Oxford, 29.-30. mars 2007

International Energy Agency Workshop, IEA Topical Expert Meeting on Radar, Radio and Wind Turbines", Amsterdam, 18.-19. November 2009

QinetiQ, Gavin J Poupart, Wind farm impact on radar aviation interests – final report, 2003

QinetiQ, Martin J Howard, Colin Brown, Results of electromagnetic investigations and assessments of marine radar, communications and positioning systems undertaken at the North Hoyle wind farm by QinetiQ and the Maritime and Coastguard Agency, QinetiQ/03/00297/1.1, MCA MNA 53/10/366, 22. November 2004

Royal Air Force UK, The effects of wind turbine farms on air defence radars, 06.01.2005

Sheringham Shoal offshore wind farm Gapfiller concept solution, E. Aarholt, Statoil ASA, International Energy Agency Topical Expert Meeting on Radar, Radio and Wind Turbines, Amsterdam 18-19.11.2009

Sintef rapport, Analysis of possible consequences of collocating Avinor's Monopulse secondary surveillance radar and wind turbines, 16.04.2004

Merill Skolnik, Introduction to Radar Systems, McGraw-Hill, 1981

US-DoD, The effect of windmill farms on military readiness, Report to the congressional defense committees, Office of the Director of Defense Research and Engineering, 2006

Wind Farm Gapfiller Concept Solution, C. A. Jackson, BAE Systems Integrated System Technologies, E. Aarholt, Teleplan, IEEE Conferences, European Radar Conference EuMW2010 proceedings, pp 236-239, Paris, Sept-Oct 2010

Abbreviations

Abbreviation	Description
ASR	Air surveillance radar
CFAR	Constant False Alarm Rate
dB	deciBell (signal strength)
dBm	deciBell with reference to milliwatt (signal strength)
FSPL	Free space path loss
GHz	Giga Hertz (radar frequency, 10^9 Hz)
IEA	International Energy Agency
µs	microsecond (10^{-6} second)
masl	Metre above sea level
MHz	Mega Hertz (radar frequency, 10^6 Hz)
MW	Mega Watt (turbine power, 10^6 Watt)
PSR	Primary surveillance radar
RAG	Range Azimuth Gating
SSR	Secondary surveillance radar