Title: "Fixed-link wind-turbine exclusion zone method"

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A proposed method for establishing an exclusion zone around a terrestrial fixed radio link outside of which a wind turbine will cause negligible degradation of the radio link performance.

Introduction

Obstruction or reflection of radio waves by a wind turbine can degrade the performance of a fixed radio link due to the effect of large blades rotating at approximately 32 rpm. Typically there are 2 or 3 blades. Thus any significant interfering signal, such as a delayed multipath component, will fluctuate in signal level around 1.0 to 1.5 Hz. This is particularly problematic to a digital link where the performance is assessed on a second-by-second basis.

Thus a special criterion for the proximity of wind turbines to radio links is considered necessary. This document proposed a practical method for establishing an exclusion zone around the path of a fixed radio link within which it would be inadvisable to install a wind turbine.

Section 2 describes the possible degradation mechanisms.

Section 3 gives the underlying bases of the proposed method.

Section 4 describes the individual calculations.

Annex 1 gives the complete method in engineering form.

Annex 2 presents example results for a 7 GHz 20 km link.

Annex 3 presents example results for a 1.5 GHz 60 km link.

Annex 4 summarised the results of a short literature search.

Summary

This paper is an attempt to propose a practical method for establishing an exclusion zone around the path of a fixed radio link within which it would be inadvisable to install a wind turbine. This is necessary due to the ever increasing number of windfarm proposals being presented to the RA, and the very large number of fixed links in existence whose performance may be degraded by a windfarm in proximity.

The paper identifies three principal degradation mechanisms which are relevant to a wind turbine in proximity to a single radio link. These are;

Near-field effects, whereby a transmitting or receiving antenna has a near-field zone where local inductive fields are significant, and within with it is not simple to predict the effect of other objects

Diffraction, whereby an object detrimentally modifies an advancing wavefront when it obstructs the waves path of travel.

Reflection or scattering, whereby the physical structure of the turbines reflects interfering signals into the receiving antenna of a fixed link.

The paper then continues to present the formulae by which the effects of these mechanisms may be analysed.

Based upon which the following statements hold true;

The magnitude of a clearance zone to minimise **Near-field effects** increases with increasing antenna diameter and also increases with increasing link operating frequency.

The magnitude of a clearance zone to minimise **Diffraction** increases with decreasing link operating frequency.

The magnitude of a clearance zone to minimise **Reflection or scattering effects** increases with increasing required C/I ratio for the reflected path and is a function of the antenna discrimination.

The paper then goes on to feed these equations with some values from fixed links at 7.5 and 1.4GHz and gives some quantitative examples for the clearance zones required for worst case examples for each of the identified performance degrading effects.

Degradation Mechanisms

There are three potential degradation mechanisms which are relevant to a wind turbine in proximity to a single radio link.

1.1 Near-field effects

A transmitting or receiving antenna has a near-field zone where local inductive fields are significant, and within which it is not simple to predict the effect of other objects.

1.2 Diffraction

Diffraction modifies a radio wave when an object obstructs part of an advancing wavefront. It should be noted that the object does not need to be a good reflector for this to happen. Diffraction effects can occur when the obstructing object is totally absorbing. Avoidance of diffraction effects can be guaranteed by requiring obstructions to be outside a specified Fresnel zone of a radio link. Fresnel zones are described below.

1.3 Reflection or scattering

The distinction between "reflection" and "scattering" is only between a coherent (mirror-like) reflection and diffuse scattering. Essentially they are the same mechanism. When a radio wave illuminates an object a fraction, possibly a large fraction, of the incident energy is re-radiated in various directions. In pure specular reflection it is wholly re-radiated in the direction of optical reflection, which can only occur from a planar surface. In practice at radio frequencies many surfaces are either curved or rough in comparison with the wavelength. The re-radiated energy may be somewhat concentrated in a specular direction, but a significant proportion often exists in other directions.

If a radio link transmitter illuminates a wind turbine and some of the reflected or scattered wave enters the receiver, the result is a multipath situation. Unless the level of the reflected/scattered signal is negligible compared to the direct signal, the combination of the signals and the time differences between their modulation may cause performance degradation.

Basis of Proposed Method

This proposal is based on the assumption that the radio wavelength is small compared with the length of the wind turbine blades. Radio calculations can thus assume that physical optics apply.

The method defines three regions around a fixed radio link within which a wind turbine should be viewed as incompatible with the link:

a) **Near-field distance.**
Numerically intensive calculations would be needed to assess the effect of a wind turbine within the near-field distance. Since it is not expected to represent an onerous restriction it is proposed that there should be an exlusion zone for any wind turbine based on a criterion for near-field distance. The calculation for a suitable near-field criterion is described in Section 4.1 below.

b) **Fresnel zone.**
Diffraction effects will be insignificant if obstructions are kept outside a volumes of revolution around a radio path know as a Fresnel zone. The calculation for a suitable Fresnel-zone criterion is described in Section 4.2 below.

c) **Excessive reflection/scattering zone.**
This is calculated such that any reflected/scattered signal from the wind turbine outside the zone will arrive at the receiver with an amplitude sufficiently smaller than the direct signal such that its effect, even allowing for the delayed arrival, will be negligible. This calculation is based on the concept of carrier-to-interference ratio (C/I), usually expressed in dB. A fixed radio link is normally designed to different values of C/I. Typically a large C/I is specified which should be exceeded for all but 20% of time, and a somewhat lower value which must be exceeded for all but a much smaller percentage of time, typically in the range 0.1% to 0.001%. The choice of C/I ratios will depend on the modulation and coding schemes of the link and the required performance. To ensure that a wind turbine has negligible effect on performance it is suggested that the calculation of reflection or scattering should be based on a C/I ratio somewhat higher than the

20% value. The calculation of an exclusion zone to protect against excessive levels of reflection or scattering is described in Section 4.3 below.

Calculation of Exclusion-Zone Distances

The following sub-sections provide additional information on the proposed calculations. At this stage it is wished to describe basic principles rather than give an engineering solution. Thus equations will use linear quantities (as opposed to dB) which can be in any self-consistent system of units.

1.4 Near-field distance

There is no absolute limit for the extent of an antenna's near field. For a horn or dish antenna the near-field distance can be taken as:

$$D_{nf} = N_{nf}\,\eta D_a^2 / \lambda \qquad \text{(self-consistent units)} \qquad (1)$$

where:

N_{nf} = 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 = diameter of antenna physical aperture;
λ = wavelength.

In view of the problematic nature of any degradation due to a wind turbine, it is proposed to set N_{nf} to the conservative value of 3.

The efficiency of a horn or dish antenna may typically be in the range 0.6 to 0.8. If the value is not known, it is conservative to assume that it is 1.0.

For other types of antenna where there is no recognisable physical aperture, the near-field distance can be estimated as:

$$D_{nf} = N_{nf}\;\lambda\, g / \pi^2 \qquad \text{(self-consistent units)} \qquad (2)$$

where:

g = boresight gain (linear)
= $10^{0.1G}$
where G = boresight gain in dBi.

However defined, the near field zone of an antenna will not in general be a sphere. The near-field distance will be different in different directions. For simplicity, and because it is believed that this will not result in impracticable restrictions, it is proposed to take D_{nf} as given by either equation (1) or (2) as the near-field exclusion distances in all directions from the antenna concerned, and to apply this criterion for both terminals of a fixed radio link.

1.5 Criterion for diffraction

Criteria for avoiding diffraction effects are normally based upon an exclusion volume in 3-dimensional space around the (normally line-of-sight) radio path of a fixed link. Such a volume is defined in terms of Fresnel zones. The n-th Fresnel is the locus of all points for which, if the radio signal travelled in a straight line from the transmitter to the point and then to the receiver, the additional path length compared to the straight transmitter-receiver path equals $n\lambda/2$, where λ = wavelength.

For large static obstructions, particularly terrain, a criterion requiring 0.6 of the first Fresnel zone radius to be unobstructed is commonly used. This should be calculated for the atmospheric refractivity gradient exceeded for perhaps 99% of an average year, which corresponds in the UK to an effective earth-radius factor of about 0.6 (rather than the median value of about 1.3).

For the varying geometry of a wind turbine it will be prudent to adopt a more conservative criterion than 0.6 of the 1st Fresnel Zone. It is suggested that to define a wind-turbine exclusion zone equal to the complete 2nd Fresnel zone would be realistic. The radius of this zone around the direct line-of-sight path of a radio link is given to an adequate approximation by:

$$R_{F2} = \sqrt{\frac{2\,\lambda\, d_1 d_2}{d_1 + d_2}} \qquad \text{(self-consistent units)} \qquad (3)$$

where:

d_1, d_2 = distances from each end of the radio path.

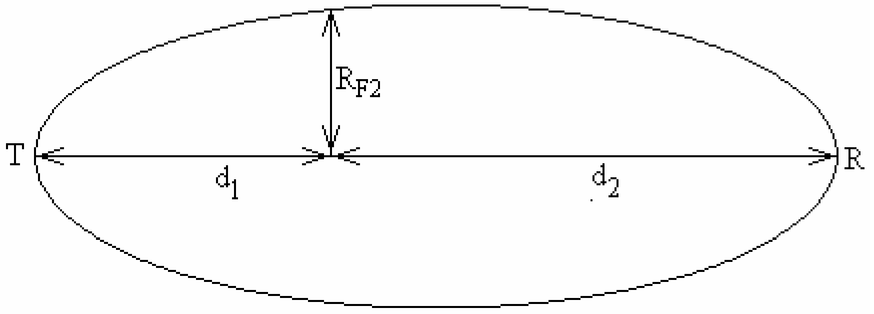

Figure 1: Approximation to Fresnel zone around a radio path

Figure 1 illustrates the general form of the zone produced by equation (3). The definition of Fresnel zone is based upon a fixed path difference between the direct and indirect paths between transmitter T and receiver R, which consists of an ellipse with T and R at the foci. As stated above, equation (3) is an approximation which clearly fails in the vicinity of the antennas. However this is not important since clearance from the antennas will be covered in any case by the other two criteria. Equation (3) is the normal method for computing Fresnel clearance around radio paths and is adequate for the present purposes.

Equation (3) thus provides a lateral clearance distance to be applied along a radio path. Although it should strictly be applied in 3-dimensional space, it will in most cases be adequate to apply it horizontally each side of the path of a fixed radio link.

It can be noted that the Fresnel clearance zone is a function of wavelength and path length only. It does not depend upon the antenna characteristics.

1.6 Criterion for reflection/scattering

The extent to which an object will reflect or scatter radio waves is usually quantified by its Radar Cross Section (RCS). This is a property of the complete object, and is defined as the area in the plane normal to the direction of illumination which, if it were to re-radiate isotropically all energy incident upon it, would produce the same effective radiated power in a given direction as actually occurs. The RCS of an irregular object is thus a function of the incident and scattered directions in relation to the shape of the object, and can vary widely as these directions are changed. It is also important to note that a RCS can be larger than the silhouette of the object as viewed from the direction of illumination.

There is little detailed information on wind turbine RCS values. An obvious problem is that these machines have variable geometry; not only do the blades rotate, but the horizontal axis of blade rotation varies in azimuth according to wind direction, and the pitch angle of the blades varies according to wind speed and electrical load. It seems reasonable to assume that there will be certain combinations of illumination and scattering angles plus blade positions which will produce a maximum RCS, but it is difficult, certainly in any direct measurement, to known whether a maximum of RCS is being observed.

The exclusion zone calculation should be based on the maximum RCS which can possibly occur, even if this may apply to a given link-turbine layout only rarely. Thus in this section it is assumed that a satisfactory estimate of maximum RCS is available.

In the absence of more reliable information it is provisionally proposed that the optical silhouette of the complete blade set of a wind turbine, as viewed parallel to the axis of blade rotation, is used as the RCS.

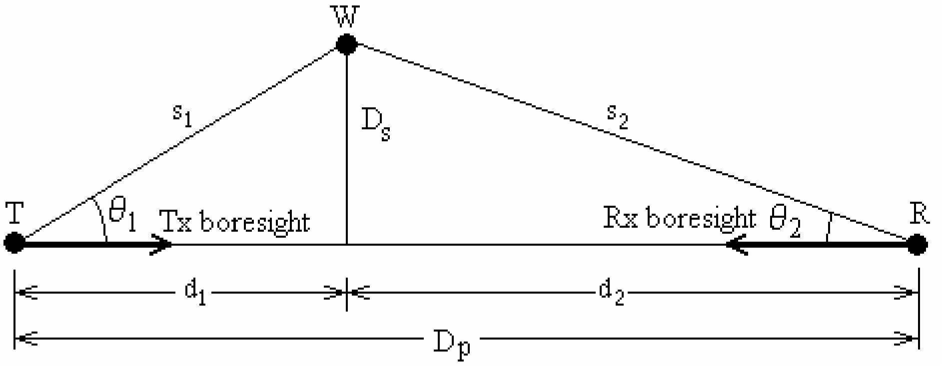

Figure 2: reflection/scattering from wind turbine affecting link between T and R

Figure 2 illustrates the geometry used in the assessment of reflection or scattering. Strictly this should be applied in 3-dimensional space around the radio path from transmitter 'T' to receiver 'R', although in most cases it will be satisfactory to treat the dimensions in the horizontal plane, that is, to treat figure 2 as a plan view.

The objective is to calculate the C/I ratio between the direct path T-R and the longer path T-W-R reflected or scattered at the wind turbine 'W'. It is assumed that:

a) T and R use directional antennas mutually aligned to maximise the direct T-R signal;
b) The radio link T-R is line of sight, and that in the worst case the paths T-W and W-R are also line of sight;
c) The reflected paths are sufficiently close to the direct path that it can be assumed that any variation of propagation due to atmospheric effects will correlate on both the direct and reflected/scattered paths.

On this basis the calculation of C/I ratio can be based on free-space propagation.

The free-space transmission loss between the transmitter and receiver antenna terminals over the direct path T-R is given in linear form (a ratio greater than 1) by:

$$l_d = \frac{p_t}{p_r} = \frac{(4\pi D_p)^2}{\lambda^2 \; g_1(0) \; g_2(0)} \qquad \text{(self-consistent units)} \qquad (4)$$

where:

p_t = transmitted power input to T antenna

p_t = received power output from R antenna

D_p = radio path distance from T to R

$g_1(0)$, $g_2(0)$ = T and R antenna gains (as ratios), the zeroes indicating boresights.

The free-space transmission loss between the transmitter and receiver antenna terminals over the indirect path T-W-R is similarly given by:

$$l_i = \frac{p_t}{p_r} = \frac{(4\pi)^3 \, s_1{}^2 \, s_2{}^2}{\sigma \, \lambda^2 \; g_1(\theta_1) \; g_2(\theta_2)} \qquad \text{(self-consistent units)} \qquad (5)$$

where:

σ = worst-case radar cross-section in units of area

s_1, s_2 = distances from T to W and from W to R

$g_1(\theta_1)$, $g_2(\theta_2)$ = T and R antenna gains (as ratios) at the off-boresights angles θ_1, θ_2.

Equation (5) shows that the loss over the reflected/scattered path will be a maximum when $s_1 = s_2$. When considering clearance distances laterally from a radio link, this means that the clearances are likely to be at a minimum around the centre of the path, and a maximum close to the terminals (transmitter and receiver). However, this general conclusion will be modified by the antenna gain patterns.

Equations (4) and (5) can be combined to give the resulting C/I ratio (as a linear ratio):

$$r_{ci} = \frac{l_i}{l_d} = \frac{4\pi \, s_1{}^2 \, s_2{}^2 \; g_1(0) \; g_2(0)}{\sigma \, D_p{}^2 \; g_1(\theta_1) \; g_2(\theta_2)} \qquad \text{(self-consistent units)} \qquad (6)$$

It can be noted that equation (6) has no frequency dependency, but is a function of the antenna radiation patterns.

Equation (6) can be used to calculate the worst-case C/I ratio resulting from a given wind turbine at a known position, which typically would be defined by distances d_1, d_2 and the side distance D_s in figure 2. If it is wished to draw an exclusion zone around the link it will, in general, be necessary to iterate equation (6) for increasing values of D_s until the required value of C/I is obtained, and to do this for different pairs of d_1 and d_2 values along the path.

Annex 1

Method for defining an wind-turbine exclusion zone around a fixed radio link

The wind-turbine exclusion zone is the outer envelope of the following individual zones.

A1.1 Antenna near-field zones

These zones consist of circles drawn round each antenna of radius equal to the near-field clearance distance D_{nf} which can be calculate by one of two methods.

For a dish or horn type of antenna with an identifiable physical aperture:

$$D_{nf} = 10\,\eta D_a^2\, f \qquad \text{(m)} \qquad \text{(A1.1a)}$$

where:

η = antenna efficiency ($0.0 < \eta < 1.0$) if known, else 1.0;
D_a = diameter of antenna physical aperture (m);
f = frequency (GHz).

For any other type of antenna:

$$D_{nf} = 0.1\ 10^{0.1G} / f \qquad \text{(m)} \qquad \text{(A1.1b)}$$

where:

G = maximum (boresight) antenna gain (dBi).

A1.2 Fresnel clearance zone

This zone sets a lateral radius from the radio path R_{F2} from the transmitter ‘T’ to receiver ‘R’ to avoid diffraction effects, as shown in figure A1.1.

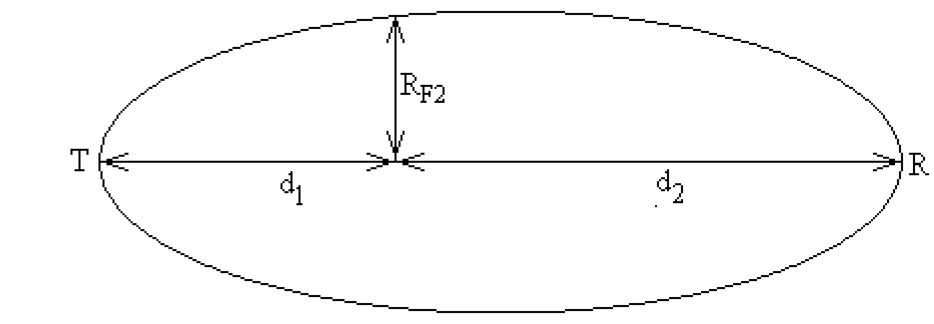

Figure A1.1: Fresnel clearance zone

The clearance distance R_{f2} at any point along the radio path is given by:

$$R_{F2} = \sqrt{\frac{600\, d_1 d_2}{f\ (d_1 + d_2)}} \qquad \text{(m)} \qquad \text{(A1.2)}$$

where:

d_1, d_2 = distances from each end of the radio path (km).
D_p = total path length (km).

A1.3 Reflection/scattering clearance zone

This zone sets a lateral distance from the radio path D_s to ensure that any multipath effects due to reflection or scattering from the wind turbine ‘W’ are negligible, as shown in figure A1.2. All distances are in km.

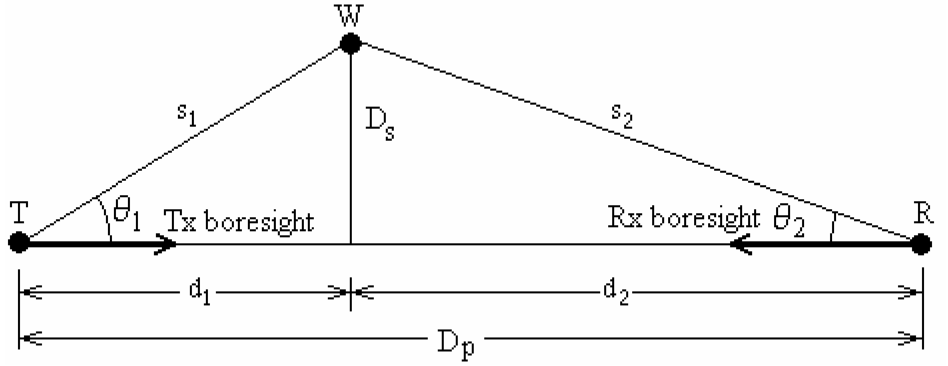

Figure A1.2: Reflection/scattering clearance zone

The ratio, expressed in dB, of the wanted signal level received from the direct T-R path divided by the worst-case signal level received from the indirect T-W-R path, is given by:

$$R_{ci} = 71 - S + 20 \log (s_1 s_2) - 20 \log (D_p) + G_1(0) + G_2(0) - G_1(\theta_1) - G_2(\theta_2) \quad \text{(dB)} \quad \text{(A1.3)}$$

where:

$s_{1,2} = \sqrt{d_{1,2}^{\,2} + D_s^{\,2}}$ (km) (A1.3a)

$S = 10 \log(\sigma)$ (dB) (A1.3b)

σ = Worst-case radar cross section of turbine(m^2)

$G_{1,2}(0)$ = Antenna boresight gains (dBi) (A1.3c)

$G_{1,2}(\theta_{1,2})$ = Antenna gain at off-boresight angles θ (dBi) (A1.3d)

$\theta_{1,2}$ = angle (D_s , $d_{1,2}$) (A1.3e)

where the function ‘angle’ represents a generalised form of arctan (D_s / d) with protection against zero-divide for d = 0, and returning a result in the range zero to 180 degrees.

For each pair of $d_{1,2}$ values, equations A1.3 to A1.3e should be used to evaluate R_{ci} for D_s incremented from zero (from a non-zero but small distance in the vicinity of the terminals) upwards in suitably small increments until the required value of C/I ratio, given by R_{ci}, is obtained. A guide as to a suitable increment for D_s is that the resulting zone should be defined by a smooth curve.

Annex 2

Results for a 7 GHz 20 km link

The following results were obtained using the method given in Annex 1 with:

Frequency	7 GHz
Link length	20 km
Maximum antenna gain	32 dBi
Antenna pattern	According to ITU-R F.699-4
Radar cross section of turbine	30 m^2
Minimum reflection/scattering C/I ratio	50 dB

Figure A2.1 shows the clearances in metres required by the Fresnel-zone and reflection/scattering criteria laterally from the radio path as a function of position along the path. It should be noted that the clearance distance is greatly exaggerated compared to the distance along the path. On this scale it is not practicable to plot the near-field exclusion zone.

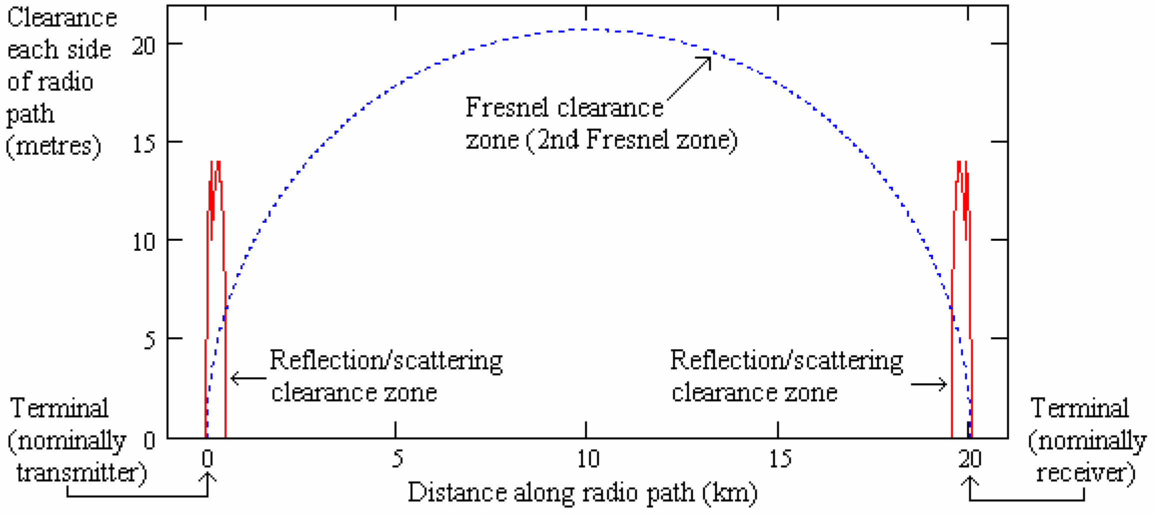

Figure A2.1: Fresnel and reflection/scattering clearances

In this case the reflection/scattering clearance distance collapses to zero within 1 km of each terminal, and is thus significant only in the vicinity of the terminals. The Fresnal clearance has its normal elliptical form, and dominates the clearance requirement over most of the path length.

Figure A2.2 shows all three clearance zones in the vicinity of one terminal, nominally the transmitter.

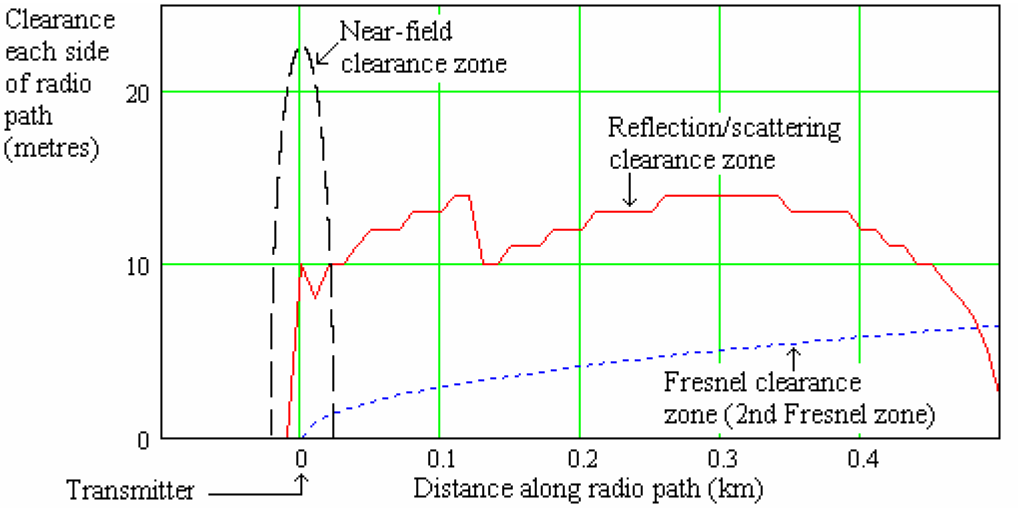

Figure A2.2 Clearance distances in the vicinity of a terminal

The difference in scale between the clearance distance lateral to the path and position along the path is now somewhat less, and it is practicable to plot the antenna near-field clearance, which is actually a circle around the antenna.

It is also possible on this scale to see the interval steps used in the iteration for reflection/scattering clearance.

The above results indicate that at frequencies of the order of 7 GHz and higher the clearances required for wind turbines are not likely to be onerous.

Annex 3

Results for a 1.5 GHz 60 km link

The following results were obtained using the method given in Annex 1 with:

Frequency	1.5 GHz
Link length	60 km
Maximum antenna gain	26 dBi
Antenna pattern	According to ITU-R F.699-4
Radar cross section of turbine	30 m^2
Minimum reflection/scattering C/I ratio	70 dB

Figure A3.1 shows the clearances in metres required by the Fresnel-zone and reflection/scattering criteria laterally from the radio path as a function of position along the path. In this case, particularly due to the larger required C/I ratio, the reflection/scattering zone completely surrounds the near-field clearance zone, which is not shown.

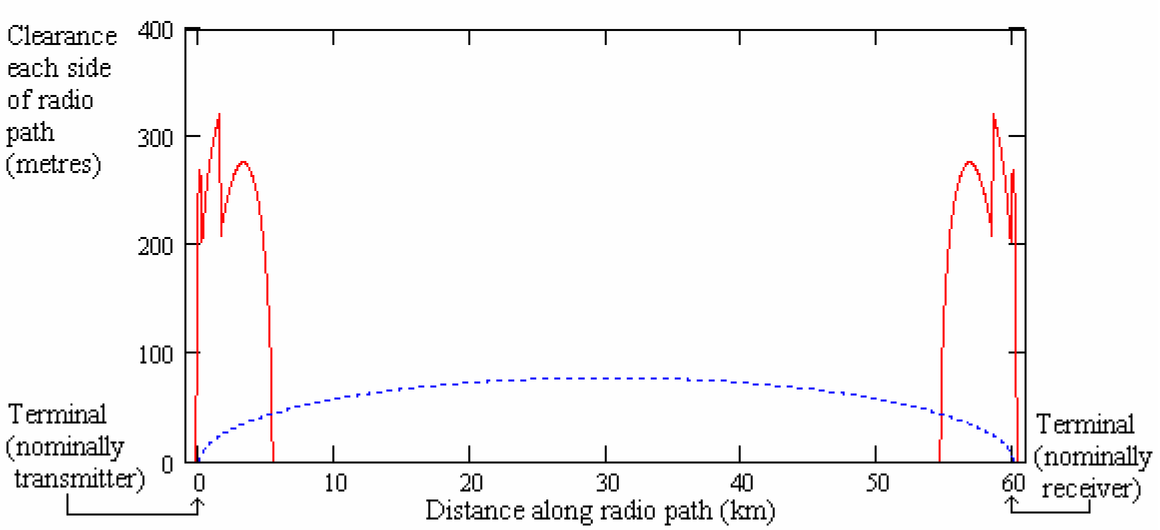

Figure A3.1: Fresnel and reflection/scattering clearances

Annex 4

Summary of Literature Search

Reference 1 is the earliest paper discovered, produced by the University of Michigan. It describes work undertaken on the problem of interference to microwave links between January 1977 and March 1978. The paper contains an analysis of the problem, a good description of the difficulties in measurement, a report of the scattering measurements undertaken on two turbine blades suspended from a crane at frequencies between 500 and 700 MHz and measurements made on a model in an anechoic chamber (scale factor about 20:1).

Reference 2 is a verbose description of the problem written by someone unfamiliar with radio engineering. It contains a comprehensive list of wind turbines available at the time of writing (probably 1985).

Reference 3 makes use of the bi-static radar cross-section to determine a cardioid coordination zone and interference zones around a wind turbine at 600 MHz. It notes that reflections from the generator housing can be as large as from a blade in the larger turbines.

Reference 4 reports on measurements using 1:20 scale models undertaken at DERA Funtington. The measurement frequencies were 3.2, 5.0 and 5.5 GHz, corresponding to 160, 250 and 275 MHz at full size. A range of bi-static radar cross-section measurements are presented and compared with theory. Good agreement was found in the specular region. Terrain modelling is described but no results are presented.

Reference 5 builds upon the work reported in reference 3, presenting a series of diagrams which allow the determination of co-ordination distance versus angle, given the bi-static radar cross-section, a fixed C/I ratio (34dB) and a frequency of 600MHz.

Reference 6 describes the effects of interference from wind turbine reflections on TV reception at 600 MHz. It also draws some conclusions as to the separations required for other services (6 km from VOR or LORAN transmitters)

Reference 7 provides a succinct precis of most published work currently available.

Reference 8 describes a series of measurements undertaken in Denmark on wind turbines of 150, 300 and 450KW sizes. Bi-static radar cross-sections were not obtained but this report is the only one to suggest that care should be taken with respect to multiple reflections from the individual members of a wind farm.

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Final Report No.2, January 1977 – March 1978

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3 **Reflections of electromagnetic waves by large windturbines anf their impact on UHF broadcast reception.**

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4 **The Provision of Guidelines for the Installation of Wind Turbines Near Aeronautical Radio Stations.**

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