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Application of the Radar Cross Section RCS for Objects on the Ground - Example of Wind Turbines

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Abstract: *Wind turbines WT are often to be located in some distance to ground based navigation, landing and radar systems. Unacceptable distortions which harm the mission of the systems have to be avoided. The minimum actual permissible distance to the system has to be determined in some way – often done by the RCS scheme for radar systems. It is recalled and shown again by theoretical as well as for numerical results that the RCS is not defined for objects on the ground if the ground is relevantly illuminated by the radar in a practically realistic finite distance. The ground as well as the near-field effect and the highly statistical behavior of the RCS in space and time for realistic distances prevent a reasonable determination and application of the RCS. Theoretical aspects as well as numerical results for wind turbines are discussed in this paper.*

1. Introduction:

Wind turbines are installed in a rapidly increasing number often due to different constraints in some distance to navigation and/or radar systems which are the focus of this paper. By that, there is a principal and classical conflict between the assigned specified task and mission of the radar and the installation of the turbines for the sake of renewable energy which has an increasing priority in the countries and societies world wide.
The problems to be solved are

- what is an "unacceptable distortion" of the radar in question? and
- how to safeguard the radar by a certain minimum distance D (Fig. 1)?

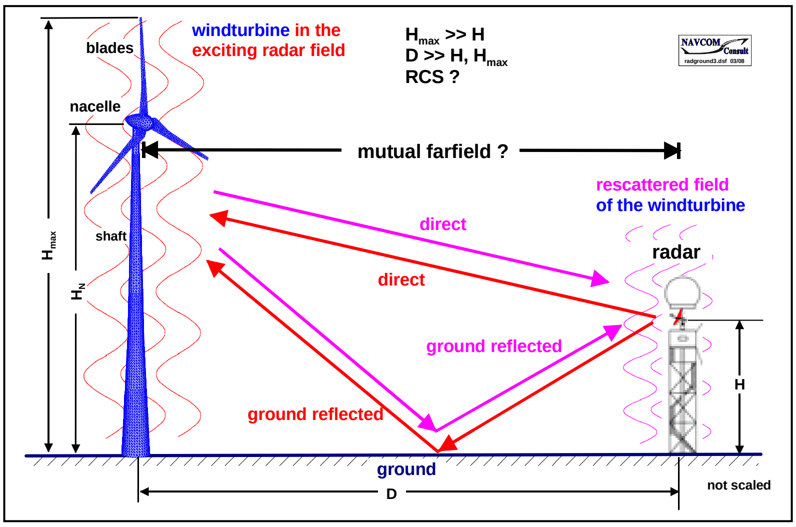

Fig. 1: Wind turbine in the radiation field of a radar above ground in some distance D

The easiest way if possible seems to be to install the turbines (sufficiently) far away. To determine this crucial distance the RCS (Radar Cross Section) is used by radar operators who are used to dealing with the RCS and who tend to stick to the RCS. It has been shown in several papers by the authors that the RCS is not applicable for objects on the ground which seems to contradict the "radar experience". This paper shall add more arguments and results to support the position of the non-applicability of the RCS for wind turbines in particular and for objects on the ground in general.

2. Radar, RCS and Wind Turbines

The Radar Cross Section RCS is a widely used classical scheme to characterize a target for a radar for the determination of the range and visibility. The RCS (σ, radar cross section; mono-static, bi-static) is defined for a plane wave excitation [1]. It is a useful parameter for objects of limited size in space such as the aircraft or other flying objects (high) above ground. The general definition of the RCS (1) [1] assumes an asymptotic infinite distance. That implies the plane wave excitation or a real far-field approximation [1],[2],[3],[4] .

$$\sigma_{pq} = \lim_{R\to\infty}\left[4\pi R^2 \frac{\left|E_p^s\right|^2}{\left|E_q^i\right|^2}\right] \qquad (1)$$

This well known formula contains the obligatory limit condition R→∞ which implies a plane wave excitation as explained also in the IEEE definition of terms explicitly [1]. The plane wave is characterized by constant amplitude and by a linearly progressing phase across the object. A single harmonic frequency is also assumed implicitly and, by that, Doppler shifted back-scattering spectrum [6] is not covered by the RCS-scheme.

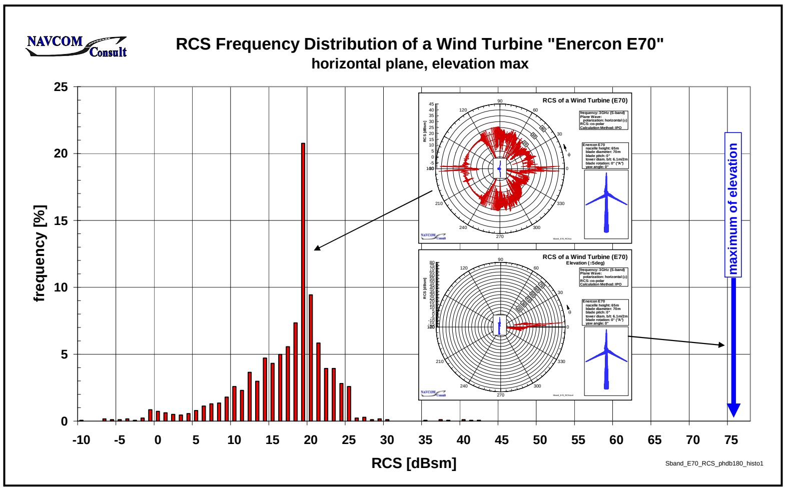

Fig. 2: Statistical frequency distribution of the RCS; small inserts in the azimuth plane (top) and elevation plane (below)

The natural consequence is that all tools for the RCS require the inherent plane wave source and in the measurements a plane wave has to be approximated. A ground plane is rejected thereof in the RCS calculation. Normally one would assume that a parameter is not used if the basic conditions for its applicability are not met for its use. But it is done nevertheless widely without knowing or appreciating the errors made obviously - why? One of the reasons seems to be that one is used to apply the radar equation [1],[2] or other derived approximate simple recipe-formulas where a non-existing single RCS-value (Fig. 2) or parameter has to be inserted, namely the RCS. It is obvious that this figure has suddenly a fully unjustified importance for the safeguarding distances which are exaggerated by the RCS-scheme.

Wind turbines are large mechanically and electrically very large complex objects having also large rotating blade structures. Besides the basic condition of the plane wave which is not met generally due to the ground interaction (Fig. 1; Fig 4 to Fig. 6), the next problem in the applied RCS is related to the scattering properties of an object in finite distances, i.e. near-field effects. The RCS is defined for a plane wave which may be approximated by far-field conditions. However, the well known far-field distance $D_F=2d^2/\lambda$ is excessively large for the wind turbines (Table 1). One has to realize that the far-field distance depends on both dimensions, of the radar antenna as well as of the electrical size of the object. Table 1 shows the very large far-field distances of the real turbines or parts of the turbines for typical radar frequencies. These are excessive and one can conclude that far-field distances can never be achieved practically in the field, even not applying only a fraction of the figures. What is the consequence? RCS figures cannot be applied for practical scenarios, i.e. turbines in distances of 5km to 15km even if the ground would not be present.

Wind turbine parameters	Far-field distance $D=2d^2/\lambda$ [km]			
	L-band	S-band	C-band	X-band
nacelle height 100m	66	200	333	666
Max height 190m	237	720	1198	2398
Blade diameter 80m	43	128	213	427

Table 1: Far-field distance of turbines for typical radar frequencies

3. Radar System Effects of Turbines and RCS; Short Discussion

Some typical and not complete effects of the turbines are

- shadowing and range reduction. The RCS-figure does not help at all. Fig. 3 shows an example of the calculation of the shadowing in free space in the back of a turbine mast for increasing distances (parameter 3km to 15km) of the radar. A normalized plane wave scattering is included. It can be seen that the field recovers faster for larger distances of the radar. More results will be shown on the conference itself.
- backscatter clutter mono-static and Doppler shifted spectrum. Static clutter will be suppressed in the radar MTI/MTD signal-processing. A comparison of 3 cases of the back-scatter for different scenarios of a pencil beam S-band radar at finite distances can be seen in the Fig. 4 to Fig. 6: free space (Fig. 4), ground included (Fig. 5) and plane wave excitation (Fig. 6; RCS). The anticipated large differences can be seen
- bistatic scattering in case of secondary surveillance radar. False interrogations or ghost targets or tracks (primary and secondary radar) cannot be analyzed by the standard mono-static RCS in general. The double bi-static analysis will be much exaggerated and seems to be unjustified.

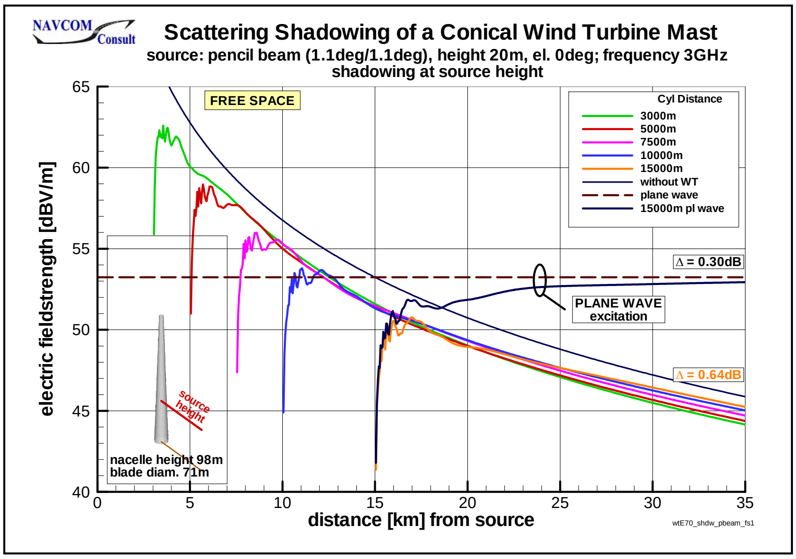

Fig. 3: Shadowing in the back of a wind turbine; S-band radar and pencil beam antenna pattern pointing to the mast. Distance of radar to mast varies from 3km to 15km. Normalized plane wave case included.

4. Summary and Conclusion

It has been shown again by basic theoretical facts that the calculated or measured RCS according to the standard definition is not applicable by fundamental theoretical reasons. A simple single RCS-figure cannot be given also due to its very wide space (Fig. 2; [6]) and time variability and Doppler spectrum characteristics [6]. Each safeguarding scheme on the basis of the RCS is by that arbitrary. Safeguarding distances are easily exaggerated depending on which RCS-figure is assigned and processed. More results and details will be shown on the conference itself. The real scattering system analysis is the solution for a realistic treatment.

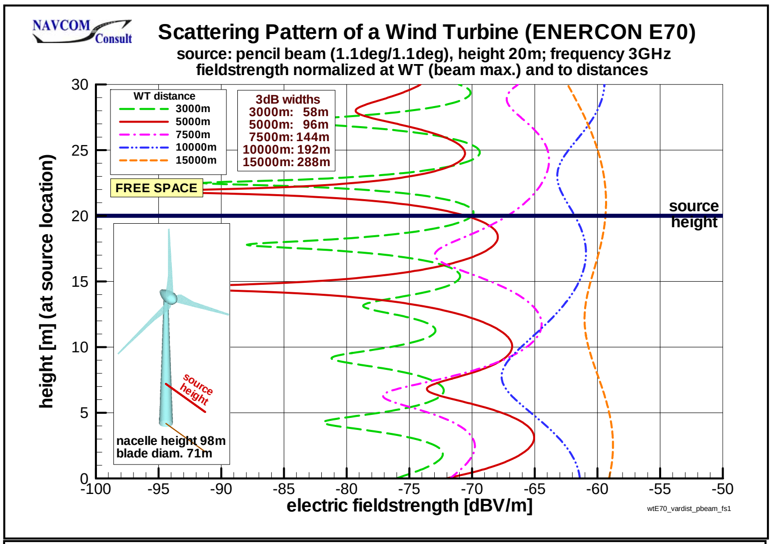

Fig. 4: Back scatter in **free space** from a wind turbine Enercon E70 back to an S-band radar; vertical trace of 30m parallel to the axis of the turbine at the source location; high gain pencil beam antenna pattern at the point of the radar; variable distances between 3km and 15km

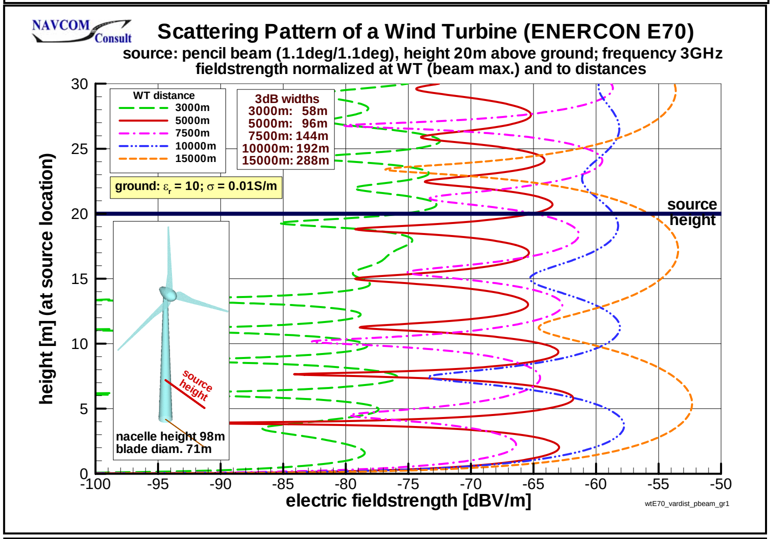

Fig. 5: Back scatter **above ground** from a wind turbine Enercon E70 back to an S-band radar 20m above ground; vertical trace of 30m parallel to the axis of the turbine at the source location; high gain pencil beam antenna pattern at the point of the radar; variable distances between 3km and 15km

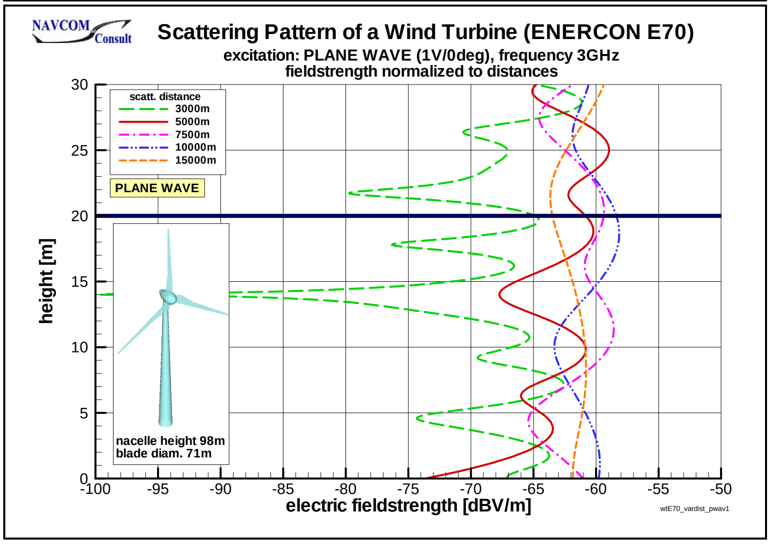

Fig. 6: Back scatter of a **plane wave** from an Enercon E70 at S-band; vertical trace of 30m parallel to the axis of the turbine analog to Fig. 4 and 5; back scatter calculated at variable distances between 3km and 15km

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