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# Wind Turbines and Radar - The Radar Cross Section RCS a Useful Figure for Safeguarding?

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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 have to be avoided. The distance to the system has to be determined in some way – often done by the RCS scheme for radar systems.
The Radar Cross Section RCS is defined for plane wave excitation. It is a useful parameter for objects of limited size in space such as the aircraft or other flying objects (high) above ground. Basic fundamental aspects are discussed by theoretical and numerical results.
Objects on the ground, such as wind turbines, cannot be described per definitionem by the RCS. Conceptional and numerical results are presented for the RCS of typical large wind turbines in different distances and for various heights of the radar above ground. The RCS has a spectrum in general and is spatially variant and also timely variant if the blades are rotating. Basic effects of the RCS above ground are shown for spherical reference objects where the standard RCS is constant.
It is concluded that the RCS cannot be used strictly speaking for the task of safeguarding.

## Introduction Wind Turbines and Radar

Wind turbines WT are constructed today more and more as part of the renewable energy program of governments worldwide. Its optimum location depends on the regional best wind scenario, but many locations depend also on the constraints and conditions of the investors. By that the locations of the WT are often more and more in some distance to existing locations of systems, i.e. navigation, landing, communication and radar systems (Fig. 1). In the context of this paper, the radar cross section RCS and its usefulness in the analysis of the impact of the WT on the radar is discussed. The radar systems can be ATC-radar, air defense radar and weather radar.

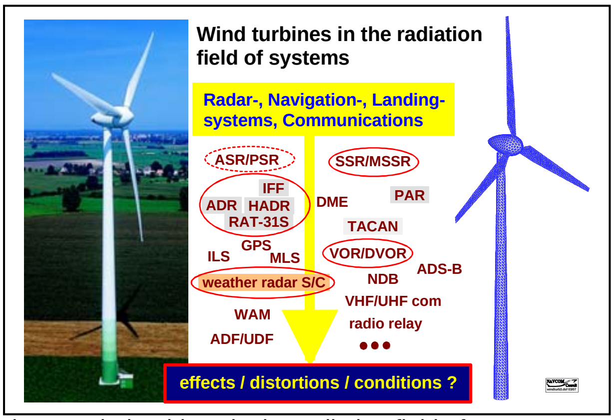


Fig. 1: Wind turbines in the radiation field of systems

## Introduction RCS

The Radar Cross Section RCS is defined for 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. It is common to characterize the objects for the radar by the RCS ($\sigma$, radar cross section; mono-static, bi-static).
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] .

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

The obligatory limit condition R→∞ implies a plane wave excitation as explained also in the IEEE definition of terms [1].
The plane wave is characterized by constant amplitude and by a linearly progressing phase across the object. 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.

An approximate RCS is published for perpendicular incidence and $A^2 >> \lambda^2$ of a square metal plate.

$$\sigma = 4\pi A^2 / \lambda^2 \qquad (2)$$

A misleading intuition and interpretation of equation (2) seems to suggest that a metal plate of double area will have a double RCS – just by adding the individual RCSs of objects such as parts of a WT or of WT in windparks.

Assume a square plate of size $A_1$ and a second plate of $A_2=2A_1$. Applying the approximate formula (2)

$$\sigma_1 = 4\pi A_1^{\ 2} / \lambda^2$$

$$\sigma_2 = 4\pi A_2^{\ 2} / \lambda^2 = 4\pi (2A_1)^2 / \lambda^2 = 4\sigma_1 \qquad (3)$$

it can be readily seen that a metallic plate of double size yields a four times larger RCS. The resulting RCS of the larger doubled area is not the sum of the individual RCS.

The reason for that is that the basic equation contains the power ratio by the squared fieldstrengths.

The following modeling and rigorous numerical calculations shall visualize that fact. A square metal plate of 2m by 2m is treated in 3 different ways for the S-band radar frequency of 3GHz:

1. RCS function of the full total plate within ±10°
2. RCS of half plate each and adding the 2 RCS
3. RCS of a quarter plate each and adding the 4 RCS

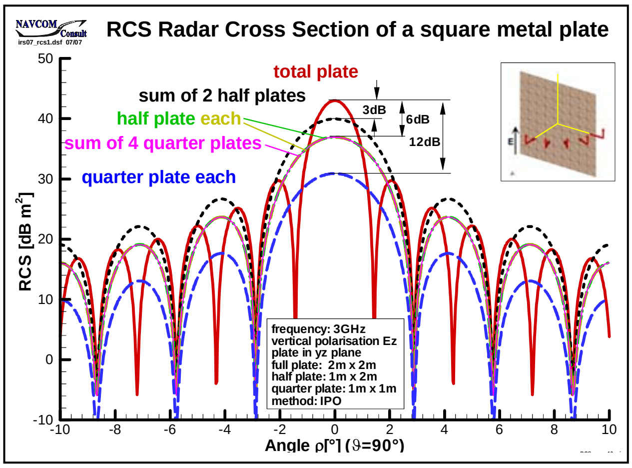


**Fig. 2:** RCS calculation of a square metal plate and subdivisions into 2 or 4 parts.

It can be easily seen from Fig. 2 that the added RCS is smaller by 3dB or 6dB respectively.

A next principal RCS-calculation (Fig. 3) shows the RCS for a rotated square plate of the same size and a second modified version where two quarters are symmetrically back setted by a quarter wave length. It can be nicely seen that at broadside the modified plate has a numerical minimum of more than 50dB where the “normal plate” has the maximum. On one hand this last result is not surprising because the RCS is the result of the normalized scattering process and is by that to be calculated by the real scattering pattern which includes the “interference effects”. On the other hand both examples show drastically that a simple addition of the individual RCS is not possible. The electrical fieldstrengths in (2) have to be added up in a complex vectorial way and have to be processed.

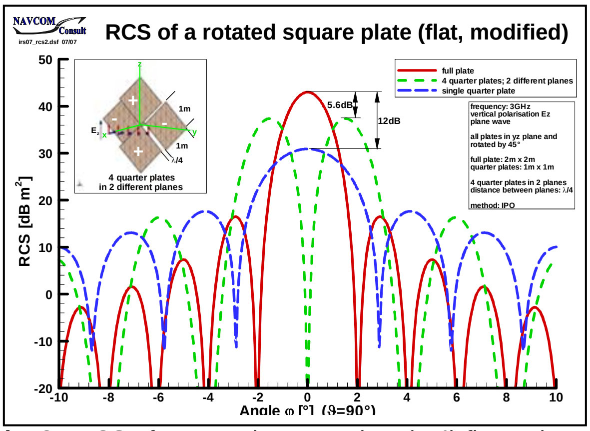


**Fig. 3:** RCS of a rotated square plate (45°) flat and modified by back setting 2 quarters by λ/4

In [2] a principal method is proposed to superpose the individual RCS and to determine the so-called “coherent RCS”

$$\sigma = \left| \sum_p \sqrt{\sigma_p}\, e^{j\Phi_p} \right|^2 \qquad (4)$$

The problem here is the phase term $\Phi_p$ - where to take the reference point in the general case of extended electrically large objects and typical higher radar frequencies. By that it does not seem to be practical. Arbitrary results can be achieved. The noncoherent RCS [2] neglects the phase term and the root and square function and is, by that, highly questionable and not applicable in any case for relatively small numbers of objects.

**Conclusions for the basic RCS:**

1. The evaluation of the RCS requires the excitation by a plane or an approximately plane wave.
2. The RCS is based on the scattered field.
3. RCS figures cannot be simply added.
4. The projected area as seen from the radar is not a measure for the RCS in general.

## RCS and Wind Turbines WT in General

As outlined above, the fundamental assumption in the definition of the RCS is the excitation by a uniform plane wave.
The wind turbines WT are naturally installed on the ground and, by that, the ground interactions have to be taken into account if the ground is significantly illuminated. In case of pencil beam antennas, such as 3D air defence radar or weather radar the lowest beam positions are relevant for the WT in most cases only.

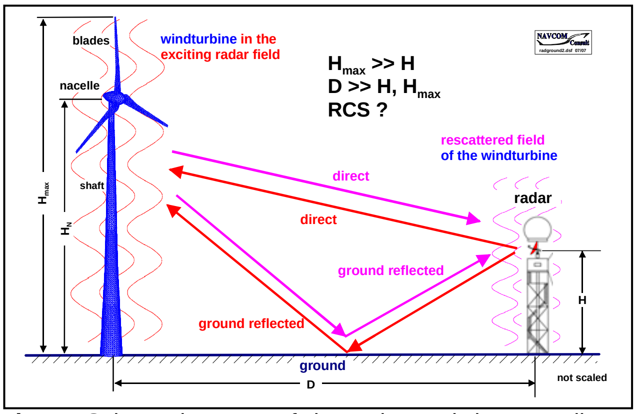


**Fig. 4:** Schematic setup of the radar and the WT, direct and ground reflected rays

The effects of the ground are twofold, for the excitation caused by the radar at the WT (Fig. 4) and for the echo response scattered by the WT (Fig. 4) at the location of the radar. The illuminating field across the object does not have a constant amplitude and does not have a constantly progressing phase. The radar has some height above ground and the WT effectively also (Fig. 4). Fig. 4 shows the non-uniform illumination schematically. Fig. 5 shows the numerically calculated variable exciting field at the location of the WT for different distances of a C-band weather radar from 3km to 30km. In the close distance of 3km, the pencil beam antenna does not even illuminate the WT completely. By all that, two sources of fundamental errors occur if the RCS-scheme is applied to the WT-case, namely

- the non-existence of the plane waves for the validity of the RCS and by that an erroneous illumination is assumed (Fig. 5)
- the distorted lobing field amplitude in the back-scattered response at the location of the radar (Fig. 6 and Fig. 7).

The amount of error of the RCS-scheme compared to the reality is unpredictable. The WT-radar-scenario has to be analyzed by appropriate tools and adequate numerical methods in a deterministic sense case by case.

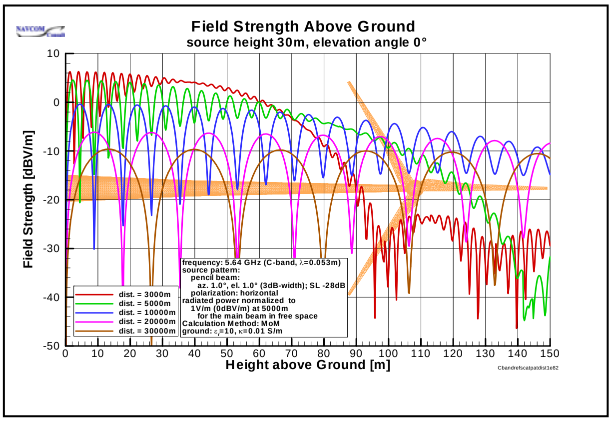


**Fig. 5:** Exciting field at the location of the WT; C-band source 30m above ground; nacelle height 109m.

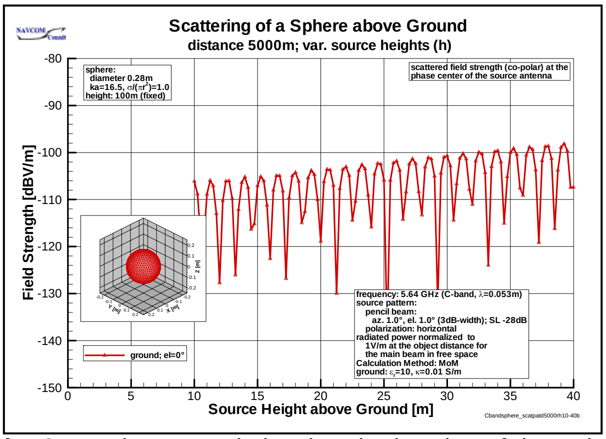


**Fig. 6:** Back scattered signal at the location of the radar having a variable height by a metallic sphere at 100m height above ground; distance of the sphere 5000m

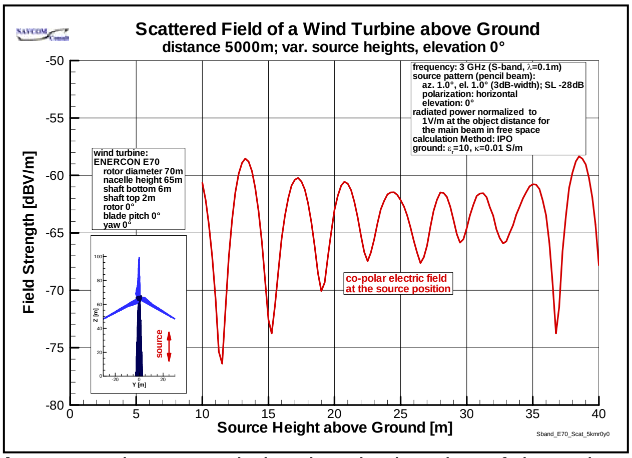


**Fig. 7:** Back scattered signal at the location of the radar of variable height by complete WT above ground, nacelle height 86m, distance of the WT 5000m

One could argue that the RCS-treatment of objects above ground would constitute the worst case. First, this is not proven and, second if so, this concept would penalize the siting of the WT and would yield unjustified large safeguarding distances.

If separately and independently calculated or measured RCS are used, the discussed effects are not taken into account. The scattering behavior of an object above ground is fundamentally different from the inherent free space condition for the standard RCS.

**Conclusions for the application of RCS:**

1. The standard numerically calculated or measured RCS in free space does not describe the physical effects for the scattering at a WT above ground.
2. The system errors are unpredictable.
3. The “worst case” concept is not justified.

## The RCS of a Wind Turbine

Although the RCS is not a justified scheme for the evaluation of the effects of wind turbines on radar in real scenarios, some detailed results for the standard RCS shall be presented and discussed in the following chapter. A plane wave excitation is assumed.

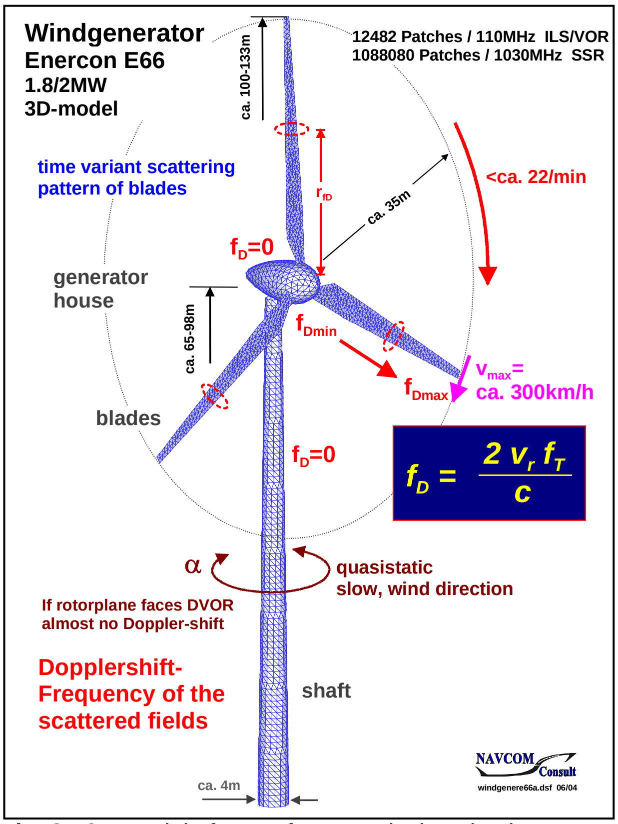


**Fig. 8:** 3D-model of a WT for numerical evaluation

The “RCS as a single figure” is sometimes requested as a basis for the safeguarding distance of the radar station. The RCS can be measured by scaled modeling or can be modeled and simulated by adequate tools. But the question arises which single RCS is a characteristic figure for the WT – assuming that the RCS would be applicable at all.

Fig. 8 shows the 3D model of a large WT to be analyzed by modern improved numerical methods [3,4,5-8]. The 3D-model is discretized and composed of a large number of metallic triangles. This is justified despite the dielectric material of glass fibre for the blades. Under strong rain conditions the water layer is almost perfectly reflecting for typical radar frequencies (L-, S-, C-band).

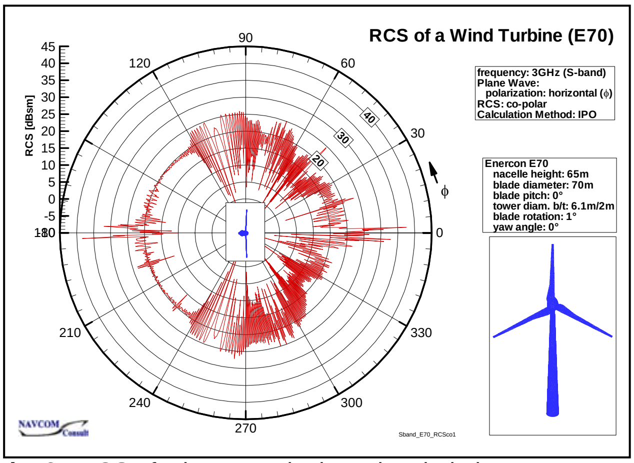


**Fig. 9:** RCS of a large WT in the azimuthal plane

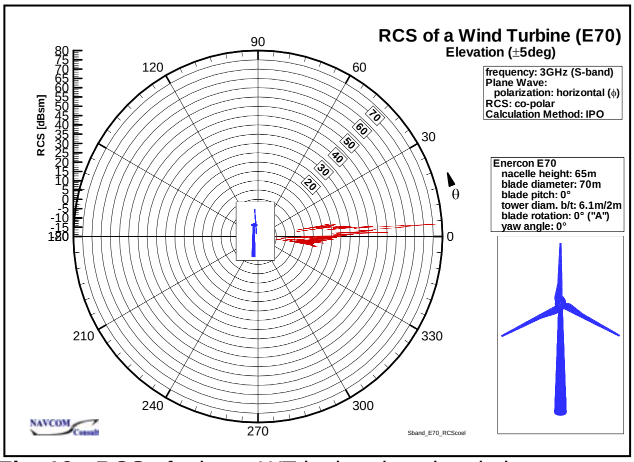


**Fig. 10:** RCS of a large WT in the elevational plane

The Fig. 9 and Fig. 10 show that the mono-static RCS of a WT in free space is extremely structured and lobed due to the electrically large size of the WT. The dynamic is at least 50dB, ranging from >70dBm$^2$ in the elevation plane when the view angle is orthogonal to the metallic surface of the mast down to 0dBm$^2$ and smaller in minima. The RCS is also very sensitive for the spatial direction. By that again, strictly speaking the RCS is different for the direct signal and the ground reflected signal also if one would use the image theory for two plane waves. Large amplitudes in narrow peaks (“flashes”) and interference are superposing an av-

erage RCS generated by the conical frequently metallic shaft. The RCS of lattice type shafts is typically much lower.
Fig. 11 shows a statistical evaluation of the RCS in the azimuth plane (Fig. 9) plus the maximum value taken from the elevation plane. The peak is some average generated by the mast as seen from that angle.

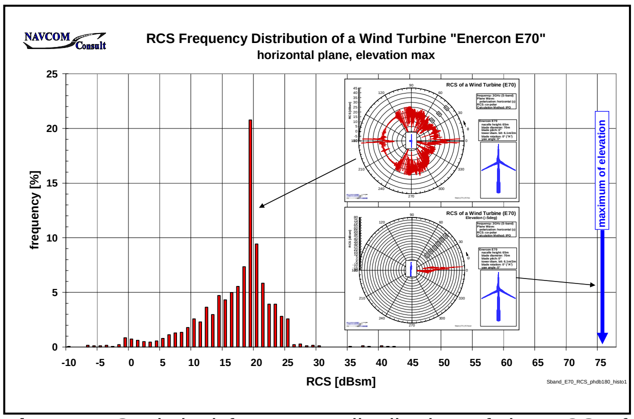


**Fig. 11:** Statistical frequency distribution of the RCS of Fig. 9 plus the maximum of Fig. 10 in the elevation plane

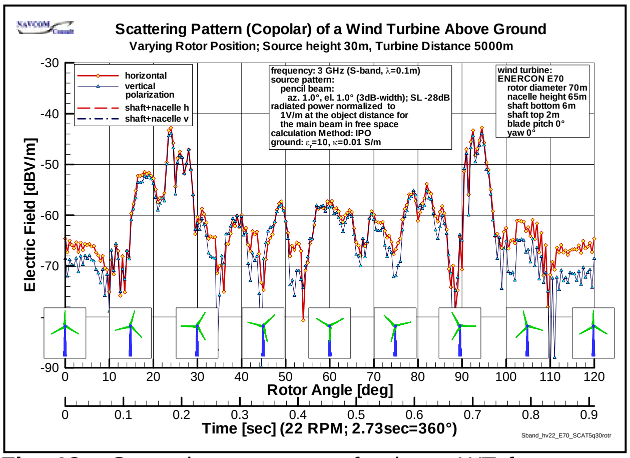


**Fig. 12:** Scattering response of a large WT from some aspect angle for a rotation cycle of 120° of the triple blades; distance 5km

Fig. 12 shows the scattering response of a large WT above ground for rotation cycle of 120° of the triple blades. The scattering response is almost independent of the vertical/horizontal polarization. Again it is remarkable that the dynamic is more than 25dB.

Fig. 13 shows a comparison of the scattering response for a fixed radar geometry (height 30m) and 2 different distances, 5km and 15km. Large differences can be observed. In the RCS-scheme the 2 cases would be identical.

A further interesting technical topic of the WT with regard to the pulse-Doppler-radar and the RCS is that of the rotating blades. The blades may rotate up to 22/min (Fig. 8). By that their radial velocity may be up to 300km/h at the tips and a high Doppler-shifted frequency spectrum will be created by the rotation (Fig. 14 ±1.5kHz; up to ca. 3kHz for a C-band radar).

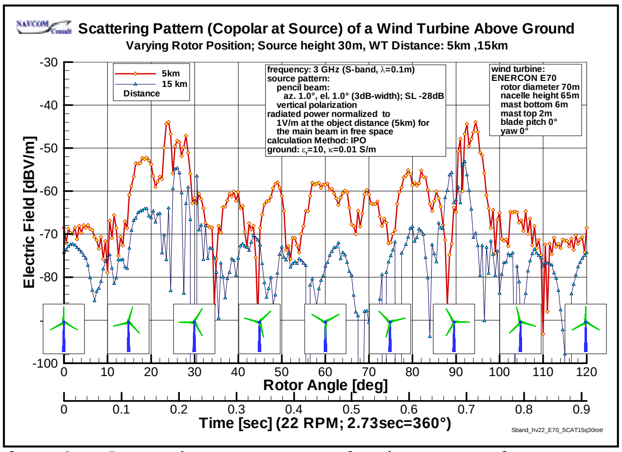


**Fig. 13:** Scattering response of a large WT from some aspect angle for a rotation cycle of 120° of the triple blades; distances 5km and 15km

The amplitudes of the Doppler shifted spectral signals depend on many factors such as the orientation of the WT and the back scattering properties of the blades. However, in any case the Doppler-shifted back-scattered signal represents a continuous spectrum and contains positive and negative Doppler shifts (Fig. 14).

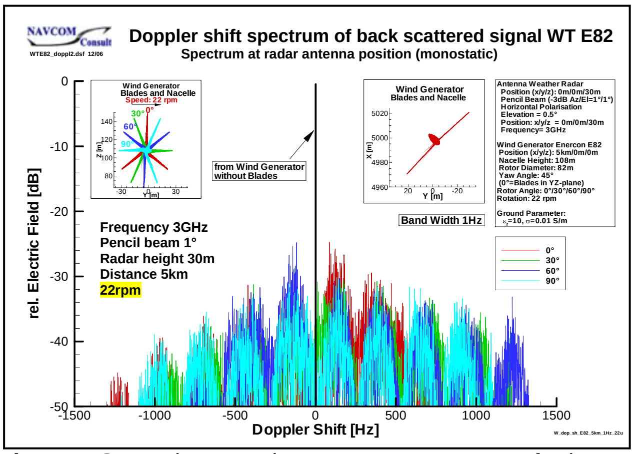


**Fig. 14:** Scattering Doppler-spectrum response of a large WT from some aspect angle for a rotation cycle of 120° of the triple blades in 4 positions; distance 5km

By that again, the simple stationary monostatic RCS of the blades is not representative for the rotating blades. In fact, the RCS is distributed and much reduced by the Doppler-spectrum spread. One can define a RCS-frequency-function in dBsm/Hz. One can understand that easily since only a small subpart of the blades creates the related Doppler frequency and not the total blade (Fig. 8). Only in case of the non-rotating stationary blades the total blades contribute to the 0Hz-signals which are suppressed by the MTI/MTD mechanism by 40dB minimum in case of modern radar.

**Conclusions for the RCS and WT**

1. The RCS of a WT has a dynamic of more than 50dB in the azimuthal plane . A total dynamic in space of more than 70dB has been observed.
2. The sharp maximum RCS is created by the metallically assumed blades in the azimuthal plane and low elevation angeles.
3. The largest RCS appear for perpendicular incidence to the metallic mast.
4. The RCS has a broad Doppler spectrum in the rotating case. The spectral lines are lower for faster rotations.
5. In the non-rotating case the RCS shows a broad frequency distribution. The statistical maximum is defined by the mast.
6. A single RCS-figure is impossible to define for a WT from a reasonable engineering point of view.

## Final Conclusion, Summary

The concept of the RCS is not applicable for objects on the ground if the ground is significantly illuminated by the radar. Fundamental theoretical and physical reasons prohibit the applicability of the RCS in the case of objects on the ground. By that it is not a useful figure and cannot be used also as a “pragmatic approximation and application” for safeguarding the radar with respect to the WT.
Since the RCS measured or calculated in free space for the required plane wave condition is not representative for the WT, these results cannot be used for the analysis and treatment of the safeguarding task. The error made in this scheme is not defined. Generally as a tendency, the safeguarding zones will be much too large when using the standard RCS depending on the single RCS-figure chosen.
The general scattering 3D-case has to be modeled and analyzed taking into account the given 3D-geometry, the antenna radiation patterns and the ground.

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