NAVCOM Consult

Fourth European Conference on Radar in Meteorology and Hydrology
Barcelona 18 - 22 September 2006

ERAD 2006

Final paper (extended summary) for publication to be included in the proceedings of the conference ERAD 2006.

Submitted by

Dr.-Ing. Gerhard Greving
NAVCOM Consult
Ziegelstr. 43
D-71672 Marbach
Germany
Tel.: +49 (0)7144 862560
Fax: +49 (0)7144 862561
navcom.consult@t-online.de
http://www.navcom.de

On the Concept of the Radar Cross Section RCS of Distorting Objects like Wind Turbines for the Weather Radar

Gerhard Greving [1], **Martin Malkomes** [2]

[1] NAVCOM Consult, Ziegelstr. 43, D-71672 Marbach/Germany

[2] Gamic GmbH, Roermonderstr. 151, D-52072 Aachen/Germany

Abstract - The applicability of the mono-static radar cross section (RCS) for the weather radar (WR) and the wind turbines (WT) is evaluated by theoretical and numerical results. It is concluded that the RCS scheme is not applicable for objects on the ground and is not a useful parameter for the definition of safeguarding distances of WT to the WR. Proposals for a deterministic case by case numerical treatment are made. Some system aspects of WT are discussed with regard to the modern signal processing of WR.

Key terms - weather radar, RCS, safeguarding distances, wind-turbines, numerical analysis, signal processing

1. Introduction

The performance of the weather radar (WR) can be distorted by objects being located in too close distances. This is also for wind turbines (WT). The WR is a special type of primary radar which measures the amplitudes and phases of the pulse response. The scattering characteristics of the WT may affect both measurement parameters. A widely used parameter for the evaluation of radar is the mono-static RCS. This paper evaluates the applicability of the RCS for a single WT in this situation and proposes alternatives for the evaluation. Since the effective distortions of a WR depend also on the radar signal processing, this subject is also discussed below.

2. Some relevant characteristics of weather radar

The WR is a special "primary radar" and has a pencil beam antenna of typical half power beam widths of 1°. The azimuthal coverage is 360. An adapted scanning pattern is defined with a periodic sequence of azimuth scans for various elevation angles. The lowest elevation angle is 0° (horizon) or often somewhat higher (e.g. 0.5°, 0.7°) or even higher. The main measurement parameters are the amplitude response yielding the cloud or rain density Z (precipitation) and the Doppler frequency shift (phase) of the pulse response yielding the average radial wind speed V and turbulence W.

Some unavoidable distortion factors may be addressed, such as the ground clutter by natural or man-made objects and aircraft and low flying helicopters having a relatively large reflectivity (RCS) and a high speed compared to clouds

Modern WR signal processing is designed for coping with these threats by MTI/MTD signal processing, averaging, smoothing or interpolation schemes, speckle removal, blanking of abnormal and unreasonable cell results and other advanced techniques. It can be anticipated that these modern measures apply also for the WT case.

3. Some relevant characteristics of wind turbines

In contrast to aircraft the WT are installed evidently on the ground. This is a fundamental difference. The typical modern WT (Fig. 1, 2) have a total maximum height of 150m (or higher) and height of the nacelle of about 115m. The blade circle has a diameter of around 80m while the shaft is mostly conical and metallic and has an upper diameter of about 2.5m. These data show the large dimensions of a WT above the ground which has a decisive impact on the scattering properties of a WT. The blades are usually made today of fibreglass material with an insert of metallic lightning protection system which is often just a metallic rod.

The WT is located in some distance to the WR and is illuminated by the weather radar

In the lowest elevation positions the WR is radiating fully towards the ground and the reflections from the ground are superposing with the direct signal (Fig. 1), thus producing an interference pattern at the location of the WT (Fig. 3). The same interference mechanism takes place for the backscattering from the WT towards the radar (Fig. 3). In smaller distances only a part of the WT is illuminated by which the relative back scattering amplitudes are much reduced.

4. The Radar Cross Section RCS in Radar

The first operational radars were air defense radars. The relatively small aircraft are detected in large distances in

---

Correspondence to : Dr.-Ing. Gerhard Greving
navcom.consult@t-online.de

space. In order to standardize and harmonize the comparative detect-ability of a target and the range of detection, the parameter RCS was "invented" to characterize different objects. In this situation the target can be treated as a quasi-point-object and the radar waves are behaving like a plane wave across the object. It is common to characterize the objects for the radar by the RCS (σ, radar cross section; mono-static, bi-static).

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

This general definition of the mono-static RCS (1) [3] assumes an asymptotic infinite distance and considers also the polarization. This implies a plane wave excitation or a real far-field approximation [3],[4],[5],[6]. The plane wave is characterized by constant amplitude and by a linearly progressing phase across the object. By that the RCS is a parameter independent of most of the radar source radiation parameters, such as gain, radiation pattern and radiated power – except the polarization. If one knows the RCS and the other features of the radar, the maximum range of detection can be estimated via the well known radar equation. For such applications the RCS is a useful concept. The targets are always much smaller than the range cells of the radar. This is not true in case of the WR.

5. Objects on the ground and radar; RCS and WR

The WR is a special type of "primary radar" intended to measure atmospheric volumetric targets. The targets of WR are typically large volumes of clouds and rain (water, ice, snow) while the targets of a "conventional primary radar" are quasi-point-objects as seen from the radar. The volumetric range cells of the WR are usually much smaller than the weather targets. That means that the "target" is assumed to be homogeneous in the volume cell defined by the range bin depth and the antenna beam. Accordingly the theory of detection and the multipath error mechanism is fundamentally different from the "conventional radar". This fundamental difference applies also to the (non-)applicability of the conventional RCS-methods for WR and objects on the ground.

The WR are naturally installed on the ground in some typical height of a WR-tower (e.g. 30m). Due to this fact, the ground interactions have to be taken into account for the lowest beam positions which are relevant for the WT only. The mono-static RCS of a WT in free space is extremely structured and lobed due to the electrically large size and structure of the WT (Fig. 5). The RCS is also very sensitive to the spatial direction of exciting plane wave. By that again, strictly speaking the RCS is different for the direct signal and the ground reflected signal also. Large amplitudes in narrow peaks ("flashes") and interference are superposing an average RCS generated by the conical metallic shaft (Fig. 5). The average RCS of lattice type shafts is typically much lower. The rotating blades also cause strongly varying re-scattering field components (Fig 6).

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. 5) at the location of the WR. By that, two sources of fundamental errors occur if a simple RCS-scheme is applied to the WR/WT-case. Namely, this is due to the non-existence of the plane waves necessary for the validity of the RCS and the distorted lobing field amplitude (Fig. 3) in the scattered response at the location of the WR (Fig. 1, 4). The amount of error is unpredictable and can be very large.

The effects of a WT have to be analyzed by appropriate tools and comprehensive numerical methods in a deterministic sense, case by case for the given geometries and the types of the radar and of the wind turbine. This includes the ground effects, which may be non-flat, and the individual dimensions and the geometry of the installations. It can be easily understood that the reflected or scattered signals depend on the illumination by the radar source. In the case of the standard simple RCS-theory, the results do not depend on the radar source characteristics. It may be proposed to apply and "save" the RCS-scheme by superposition of the radar and its image in both directions, illumination and back scattering. However, this assumes that plane wave conditions are applicable for both sources. But, this is not met generally as shown.

6. General Types of Distortions of the WR by WT

The following general potential sources or types of distortions are listed and shortly discussed

- Shadowing by the wind turbine creating precipitation errors in the lowest elevation positions: It can be easily shown theoretically as well as numerically that this is not a main in realistic scenarios. The real net shadowing error of the non-absorbing wind turbines is much smaller than the unavoidable maximum amplitude measurement error of the WR (about 1dB). The overall system error is much larger. By that the real shadowing error is negligible if the WT is in some minimum distance of e.g. 5km. This error is also much smaller than the effects of the ground on the effective antenna pattern. Numerical results will be shown on the conference. Geometrical optics based estimates assuming full blockages are misleading.
- Clutter signals generated by the stationary parts of the WT: The MTI/MTD processor will suppress these components by at least 40dB or 50dB for modern Magnetron or Klystron transmitters respectively.
- Doppler frequency shifts of the backscattered signals from the blades which may create wind speed errors: Depending on the resolution of the MTD-processor (typical 0.5 to 1m/sec out of typical 30m/sec max unique wind speed) the effective back scattering of the rotating blades is very much smaller than the back scattering in the stationary situation. See also the next paragraph.

7. Doppler shift and weather radar

An interesting technical aspect of the WT with regard to the pulse-Doppler-WR and the "RCS-behavior" are the rotating blades. This issue is sometimes discussed as to be the major threat of the weather radar by wind turbines.

The blades may rotate up to 22rpm. By that and the maximum radius of the blades of about 35m the radial velocity may be up to 300km/h at the tips. A high Doppler-shifted frequency may be created by the rotation (up to about 3kHz for the C-band WR). Typical WR measure a maximum wind/cloud speed uniquely up to about 110km/h having a typical real resolution of the speed of about 0.5 - 1m/sec. The amplitude of the Doppler shifted signals depends 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 shift frequency components at a known position of the WT. By that again, the simple stationary mono-static RCS of the blades is not representative for the rotating blades if the Doppler shift issue is evaluated. In fact, the RCS is distributed over the entire Doppler frequency spectrum and by that much reduced by the Doppler-spectrum. Results will be shown on the conference. One can define a RCS-frequency-function in dBsm/Hz. One can understand that easily since only a small subpart of the blades re-scatters the related certain Doppler frequency and not the total blade. Only in case of the non-rotating stationary blades the total blades contribute to the 0Hz-signals which are suppressed by the MTI/MTD clutter suppression mechanism by 40/50dB minimum in case of modern radar as explained before.

Herewith, trials to reduce the RCS of the blades are not necessary for the WR also.

8. Numerical Simulations; Measurements

The presented numerical results are calculated with the aid of an advanced improved physical optics method (IPO; Fig. 3 and 5) or by the methods of moments (Fig. 4). The former is in fact an improved and extended method of physical theory of diffraction. The 3D-model of the WT (Fig. 2) is consisting of a large number of metallic triangles. The blades are treated under worst case aspects also as to be metallic. This approach approximates the rain conditions also. The deterministic scattering performance including the ground can be calculated (Fig. 6) as well as the free space RCS-function (Fig. 5).

The measurement of the RCS of the isolated WT in free space is also highly questionable as outlined before for the theoretical treatment because the omission of the ground does not allow significant conclusions for the given operational scenarios. In addition the RCS is very much dependant on the

- aspect angle caused by the direction of the wind
- position and pitch angle of the rotor blades

Which model of all the possible scenarios shall be taken for the measurements?

9. Weather Radar System Aspects

The modern signal processing of the WR has to cope anyhow the distorting effects, such as the ground and the aircraft.

In a simplified view, a WT can be seen as a clutter or spurious echo for the WR. Typical modern weather radar signal processing systems have correction schemes in real time [7] among further methods for

- Clutter, stationary echoes with non-zero spectral distribution
- Sub-clutter visibility using FFT and DFT processing
- isolated polluted cells – speckle filtering
- Thresholding of echoes with bad
  - Signal to noise ratio S/N
  - Coherency SQI (signal quality index)
  - Clutter to signal ratio
- Time and range averaging
- Spectral adaptive processing in DFT mode
- Statistical clutter processing
- Clutter map methods for the known position of the WT.

All these methods can be used in real time to cope with the WT target echoes. Additionally image data processing algorithms can be used to interpolate the polluted echo cells in 2D or 3D raw data. Finally smoothing and continuity checking algorithms will eliminate the unwanted echoes which may be generated by WT in a certain WT-WR scenario.

10. Conclusion, Recommendations

It is outlined by theoretical and numerical results that the RCS does not have a meaningful application for objects on reflection planes, such as for the WT above real ground. The fundamental theoretical reasons are due to the fact that the assumed plane wave excitation is not given due to the interference of the direct and ground reflected signals. This interference mechanism takes place also for the back-scattering signals. The Doppler-shift components of the back-scattered signals are very much reduced by the spread of the back-scattering into the Doppler spectrum. The stationary RCS again is not applicable for the rotating blades. Safeguarding distances of WT to WR should not be based on the RCS due to the unpredictable relevance in a given case. As an operational consequence it seems to be obvious that the safeguarding distances are much too large on the basis of the RCS. Each case or scenario has to be analyzed by appropriate numerical system simulations. More numerical results will be shown on the conference.

Also it is outlined that modern signal processing for WR can be applied additionally to cope the effects of the WT and to improve significantly the acceptance of the WT.

11. References

[1] GREVING G. Numerical Analysis of the effects by scattering from objects on ATC-radar and various methods for its reduction - Theory, results; IRS 2006, Krakow/Poland

[2] GREVING G. Numerical Simulations of Environmental Distortions by Scattering of Objects for the Radar - SSR and flat roofs, RCS and windturbines, EURAD 2006, Manchester/UK

[3] IEEE STD 211-1997, Definition of terms

[4] SKOLNIK Radar Handbook, McGraw Hill, Boston 1990

[5] LO Antenna Handbook I, Chapman&Hall, NewYork 1993

[6] SAUVAGEOT Radar Meteorology, Artech, Boston 1992

[7] MALKOMES et al The primary ATC weather radar channel - ENIGMAIII weather extractor ff, ERAD 2006, Barcelona/Spain

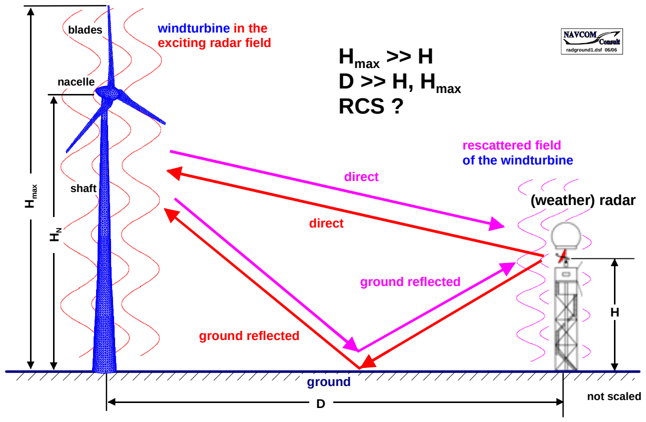

Fig. 1: Schematic of the WT in the radiation field of a WR above ground; direct and ground reflected components occur for both directions,

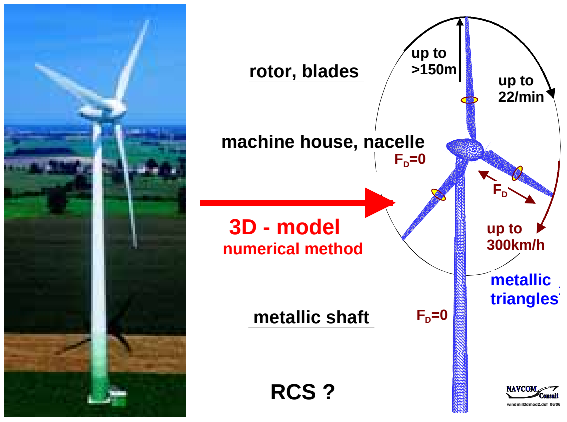

Fig. 2: Real windturbines and 3D-model associated with the numerical method for the scattering analysis

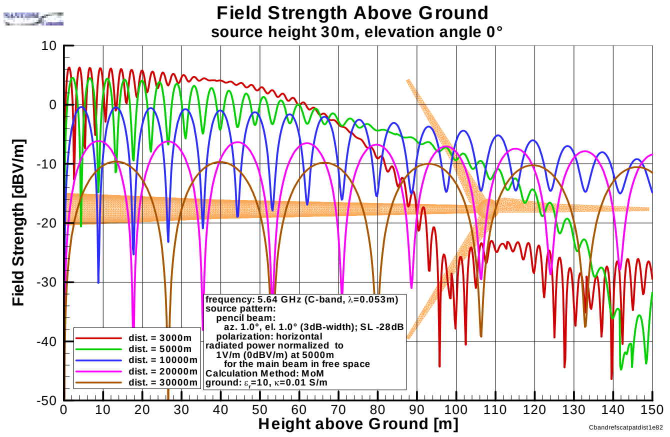

Fig. 3: Numerically calculated exciting field at the location of the metallic wind turbine for different distances of the C-band weather radar (3,5,10,20,30km); flat ground/earth assumed; horizontal elevation of the radar beam; in the shorter distances of 3km and 6km only a part of the wind turbine is illuminated;

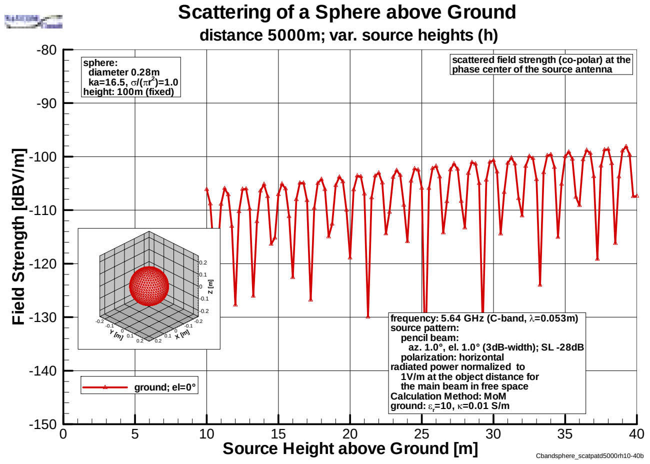

Fig. 4: Numerically calculated re-scattered field of a metallic sphere (height 100m above flat ground, distance 5km to weather radar , diameter 28cm) at the location of the C-band weather radar having a variable height between 10m and 40m;

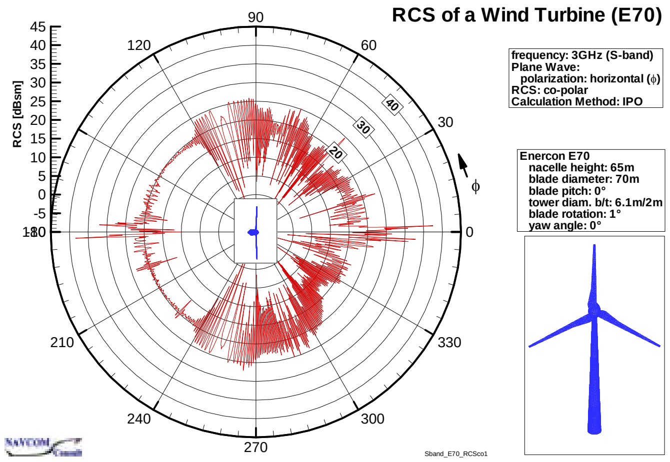

Fig. 5: Copolar Radar Cross Section RCS of a fully metallized WT in the horizontal plane.

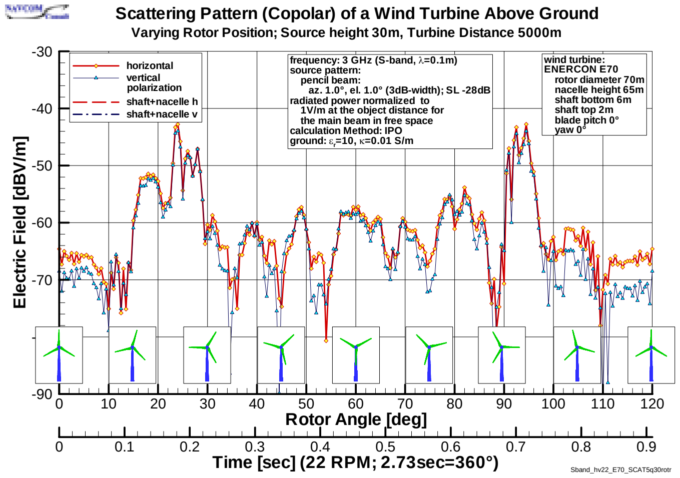

Fig. 6: Numerically calculated re-scattering of a WT at the location of the WR in a height of 30m for varying blade orientations