Weather Radar and Wind Turbines - Theoretical and Numerical Analysis of the Shadowing and related Precipitation Error

Gerhard Greving [1], Martin Malkomes [2]

(1) NAVCOM Consult, Ziegelstr. 43, D-71672 Marbach/Germany; navcom.consult@t-online.de
(2) Gamic GmbH, Roermonderstr. 151, D-52072 Aachen/Germany; info@gamic.com

1. Abstract

As part of the renewable energy concept, wind turbines WT are built in increasing numbers often in some close distance to radio based systems, such as weather radar WR. WT may have effects on the raw data of WR data due to its pulse scattering properties, i.e. the time dependent amplitude and phase or Doppler frequency measurements and polarization properties. The safeguarding distances are determined to reduce the effects to acceptable limits often on the base of crude approximations and providing undetermined large margins.

This paper deals with the general effect-theory and in particular with the "blocking " or "shadowing" of WT generating in case precipitation errors in the back of WT. It is shown that the real shadowing effects are related with the characteristics of the meteo-objects, namely its homogenous and voluminous features where the meteo-objects are much larger than the half-power-beam-widths of the WR-antenna and the radial bin-length. By that the effective shadowing is determined by the integration of the interference field in the reference planes. It is shown by systematic numerical simulations that the effective integrated shadowing is much smaller as usually anticipated and decays very fast down to acceptable limits in realistically small distances. A comparison with measurements is shown for a 4 week rain accumulation confirming in principle the simulation results.

***Key terms** - weather radar, wind turbines, distortions, numerical analysis, signal processing, shadowing, precipitation error*

2. Introduction

WR are a special type of "primary radar" ([2], [4]) relying basically on the back scattering of the radiated energy at the objects to be detected (Fig. 1). The WT (Fig. 4) are installed on the ground at a priori known locations and are practically lossless scatterers [3]. By that the WT are part of the ground clutter to be suppressed primarily by the radar internal clutter suppression schemes, also by the WR. "Normal" primary radar, such as air traffic control or air defense radar detect point-like targets whereas the WR detects voluminous objects which are treated to be homogenous and much larger than the resolution cell or "bin" (Fig. 1). Within the clutter suppression means, standard primary ATC-radar responsible for the critical air-traffic safety do have at the end the designed and integrated so-called Range-Azimuth-Gating RAG basic mitigation measure where resolution cells are blanked out which are useless by clutter. This basic RAG-scheme can be applied in principle also for the WR raw data as well.

The WR are also installed on the ground in some height (Fig. 2). By the earth curvature the coverage deep above the ground is very limited in range. By that the potentially affected volume V_{WT} by the WT close to the WR is very much smaller than the total coverage volume V_{cov} and, also, very much smaller than the volume V_{no} where the WR cannot detect the weather phenomena at all (Fig. 2). Often, the service provider of each radar asks for a safeguarding area as large as possible under preventive aspects, requesting often fully unrealistically "no effects" at all by WT. However, also more and more wind turbines WT are planned and installed as part of the political European target for renewable energy in close distances to the radar due to the lack of space and due to the advantageous locations. The WT constitute a potentially distorting scattering object (Fig. 1-3) and have the potential to produce increasingly larger effects (or in case distortions) in closer distances to radar. The conflict between these diverging interests is immanent.

This actual paper deals shortly again with the associated technical issues of effects and its analysis and in case of its mitigation in a series of papers on previous ERAD-conferences by the authors ([5], [9], [10]).

In case of an application of a WT or of a wind park, an approval has to be granted by the building authority. This paper gives some information and some guidelines and clarifies the shadowing issue.

The general effects of the WT for WR are basically known

1. ***Shadowing*** or ***Blocking*** which may result in rain rate errors in the back or in mis-interpretations of the measured data. The realistic treatment of shadowing is the main topic of this paper.

2. ***Reflections back to the WR from the stationary and rotating parts*** as part of the ground clutter. The back scattered pulses contain a Doppler spectrum depending on the rotation rate and of the spatial orientation on top of the stationary zero-Doppler back scatter from the mast and the hub. This effect can be described also generally as "***visibility***" of WT. However, the "visibility" of objects is the basic task of each radar and cannot be qualified as a distortion a priori and generally. Unwanted objects are generally simply "clutter" (see above). The stationary zero-Doppler

clutter is suppressed by at least 50dB in modern WR. These effects are often characterized on the base of the “Radar Cross Section” RCS-scheme. It has been shown by the authors that the RCS-scheme is not applicable in a strict sense ([5], [6], [7] despite the wide application by some meteo organisations. The illuminated ground prevents the required plane wave condition and the distances of the planned WTs are always within the nearfield (Table 1) of the WR.

The global signal and data processing chain is depicted in Fig. 3. Many of the modern WR today are digital dual polarized pulse Doppler WR and integrated into a WR network general often some useful redundancy. *Effects* on the WR can be claimed to be (unacceptable) *distortions* only if the final WR products are affected significantly after the complete signal and data processing chain (Fig. 3) and ***exceeding significantly the inherent system tolerances***. The status of “unacceptable distortions” has to be proven by adequate procedures and state of the art methods. The pure visibility of the WT on the analog raw data radar screen in large distances (e.g. 30km and in case much more) is certainly not a “distortion” which would today justify a rejection of an application of a WT. On this raw data level, WT may even be seen by WR in a distance of 50km and more depending on the scenario.

3. Statistical and relative aspects

The WT occupies at least one resolution cell (“bin”, V_{WT}) of the WR. The relative size is determined by the beam widths of 1° by 1° and by the cell depth which is determined effectively by the pulse length (short pulse typically 0.8µs). In typical distances of 5km or 10km for a WT the radar resolution cell has a cylindrical size of 87m or 175m diameter and a length of 125m. It is very obvious that that this absolute cell size is very much smaller than the total omnidirectional coverage volume V_{cov} (Fig. 2) and also very much smaller than that omnidirectional volume V_{no} (Fig. 2) where the WR cannot detect the weather phenomena at all due to the earth curvature. Due to the extremely small relative size of the affected volume V_{WT} compared to the total coverage and in particular to the “no-seen” volume, the real relative loss of data would be also relatively very small in case of data blanking as realized for example in the safety critical ATC-radar by the RAG-clutter-map-scheme. It must be emphasized clearly again that the WR cannot detect at all the weather phenomena down at ground where the WT are installed beginning roughly in a distance of 50km depending on the installation scenario. For larger distances up to the coverage boundaries (e.g. 200km; Fig. 2) the WR is “blind” up to a relative ground related height of more than 2km even if the refraction effect is taken into account.

An optimized 3D-interpolation would improve the situation sufficiently compared to the blanking scheme within the normal radar tolerance boundaries if the blanking seems to be not desirable.

4. Scattering, Interference fields, volume target

The WT are installed on the ground and the WT are illuminated by the radiated WR pulses (Fig. 1). The generated currents on the lossless and metallically assumed WT (Fig. 4) generate in turn the scattered field which superposes with the directly radiated radar field. The WT does not absorb electromagnetic energy from the radar field. Both partial fields have its complex field components (amplitude, phase) and polarization characteristics. If the field components are in-phase they add up in this field point or spatial region. If the components are out of phase they subtract.

The system simulations according state-of-the-art principles are able to calculate this scattering and superposition process in each field point within the halfpower beam width of the WR for each reference plane in space. The interference process generates a superposition pattern (Fig. 5, Fig. 6) where the superposed fields are in some parts (much) larger in other parts (much) smaller than the un-affected radiation field of the WR (Fig. 7). It must kept in mind that the illuminated ground creates some significant lobing in the elevation pattern for the lowest elevation beam already without the presence of WT. The received energy after reflection at the homogeneous volume target is averaged by integration. The integrated average is much smaller than the local maximum deviations from the un-affected radar field. These non-integrated maximum relative interference minima cannot be taken as to be representative for the shadowing or blocking effect of a WR. In particular optical shadowing principles yield wrong results. The energy difference between the free space radiation and the affected case by the WT is called “***scattering loss***”. It is in fact the in-balance between the positive and negative deviations in that distance in the reference plane within the half-power-beam-width of the WR-antenna.

5. Numerical Results for the effective shadowing

Systematic field calculations are shown in Fig. 7, and Fig. 8 for increasing distances of the WT to the WR, namely from the minimum distance of 1km to 15km, while the WR is located in a height of 39m and radiates with its maximum towards +0.5°. It can be seen clearly that

- the field reduction is deeper behind the WT the closer the distance between the WR and WT
- the field reduction is wider than the geometrical mast (see Fig. 7 where the scaled WT is marked)
- the interference effects are generally smaller as expected for the larger distances and the span between the maxima and minima is smaller.
- the affected portion of the main beam is increasingly smaller for larger distances.
- in the modeled and analyzed scenario the main beam sees only the mast up to a distance of 2km.

The integrated average scattering loss for each considered distance of Fig. 8 is shown in Fig. 9. It can be seen clearly that in small distances the scattering loss is increasing very fast to certainly unacceptable numbers. On the other hand the scattering loss decays also very fast to small numbers which are in the order of the “normal radar tolerances” for increasing distances. It is concluded that depending on the actual scenario the “scattering loss”, i.e. the precipitation error, should be acceptable for large WTs at a distance beginning at about 2km to 3km.

This general conclusion is confirmed by a measurement published by DWD for the WR Emden. Four very large WTs are installed in a very close distance to this WR (Fig. 9). The minimum distance is 835m only. Fig. 10 shows that the closest WT creates a clear radial shadowing effect on the accumulated rain measurement. However, for the fourth large WT (distance 2.06km) a relevant effect is hardly visible even for this very large wind turbine where the tip is seen from the WR at +2.7°. The tip of the closest WT is seen from the WR at +9.9°.

6. Summary

It has been outlined that a WR is basically a normal primary radar, but having some special features and a dedicated signal- and data processing. WTs are also for the WR a special ground clutter type at known locations. These facts can be used to suppress the clutter effects either by a RAG-application or by adapted clutter suppression algorithms ***sufficiently***. It has been shown that the real effective shadowing by the WT has to be processed and adapted to the volume target features of the meteo objects. By that the effective shadowing, i.e. the average precipitation error within the half-power beam-width, is much smaller than the maximum figures. The remaining effective precipitation errors decay very fast to acceptable and not measurable limits, e.g. <1dB. Some guidelines are given along the analyzed scenario. By the presented results it is understandable that WT can be accepted at closer distances compared to some published guidelines, e.g. 15km or 20km.

7. Acknowledgment

The numerical simulations in this paper have been carried out by Mr. Biermann and Mr. Mundt of NAVCOM Consult.

8. References

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Wind turbine parameters	Farfield distance $D=2d^2/\lambda$ [km]			
	L-band	S-	C-	X-
nacelle height 140m	130	392	784	960
Max height 200m	267	800	1600	2666
Blade diameter 120m	96	288	576	960

Table 1: Far-field distances of very large WT for typical radar frequencies

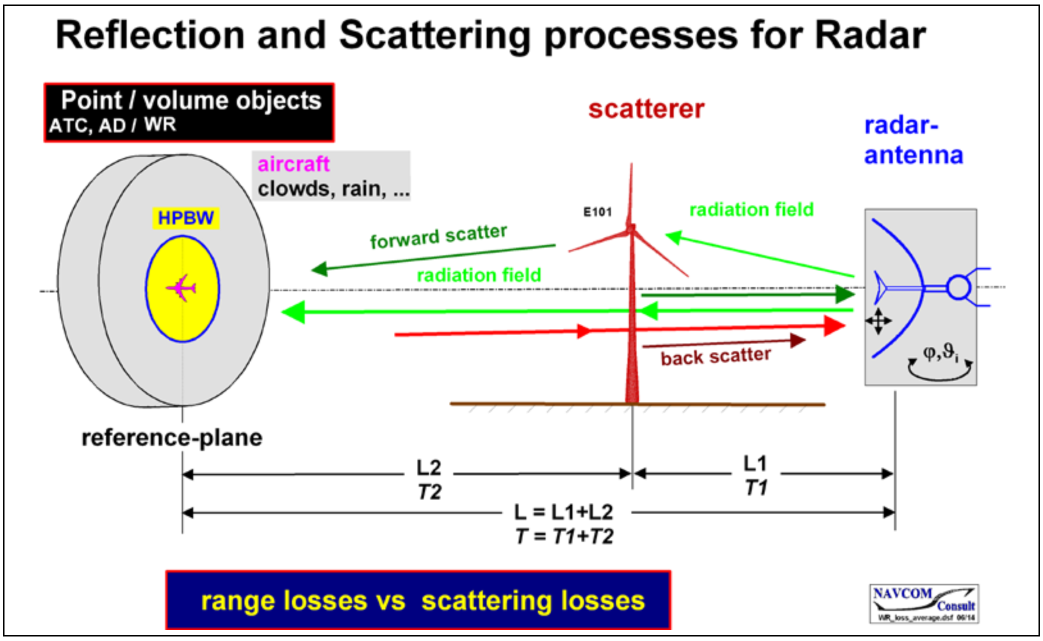

Fig. 1: Schematic diagram of Radar and the scattering process at a scattering object (Weather Radar WR, ATC, AD)

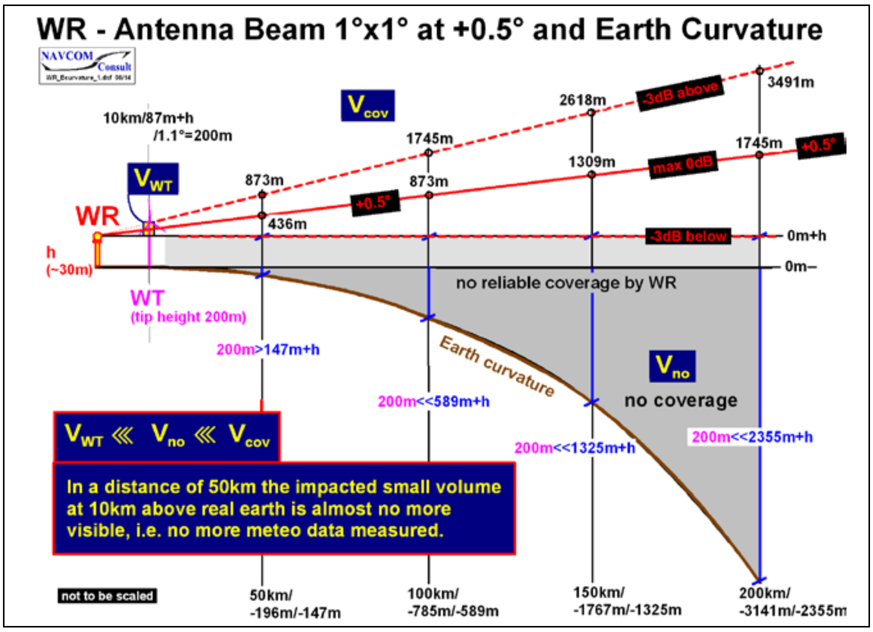

Fig. 2 WR , Antenna beam and earth curvature; coverage aspects

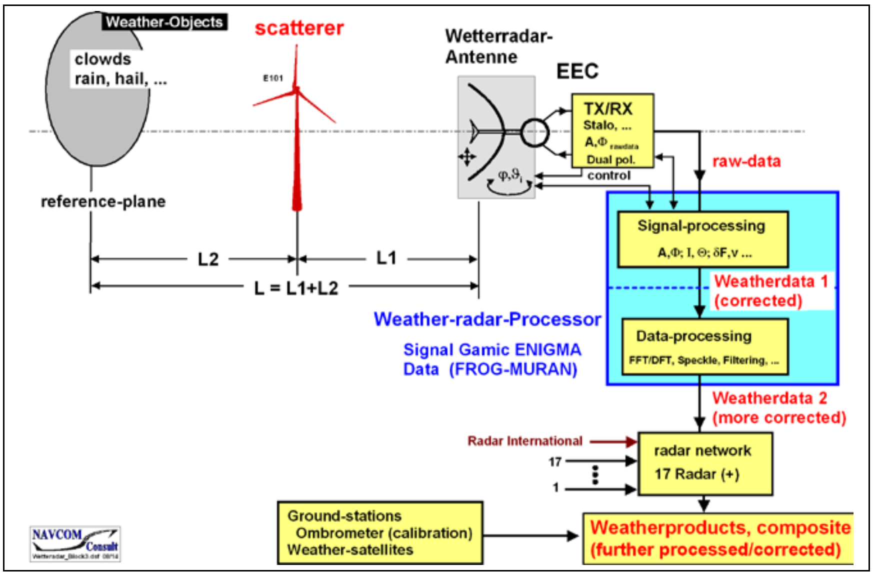

Fig. 3 Functional scheme of a modern WR and network; scattering scenario; signal- and data processing chain

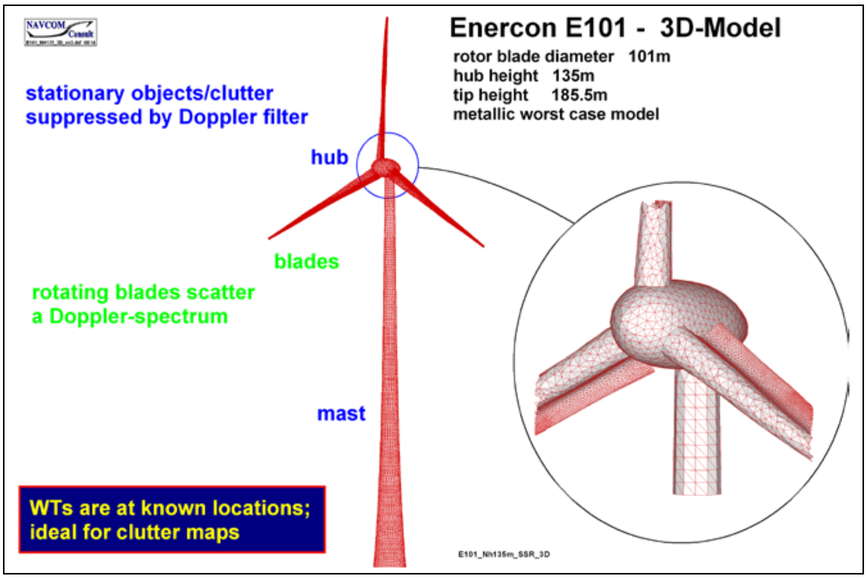

Fig. 4: Numerical 3D-model of a very large WT

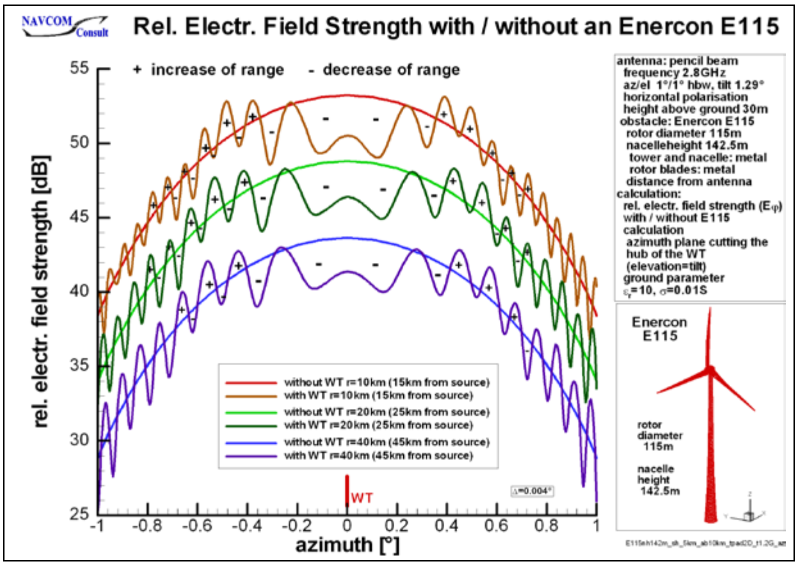

Fig. 5: Azimuthal WR interference effects in the back of a WT

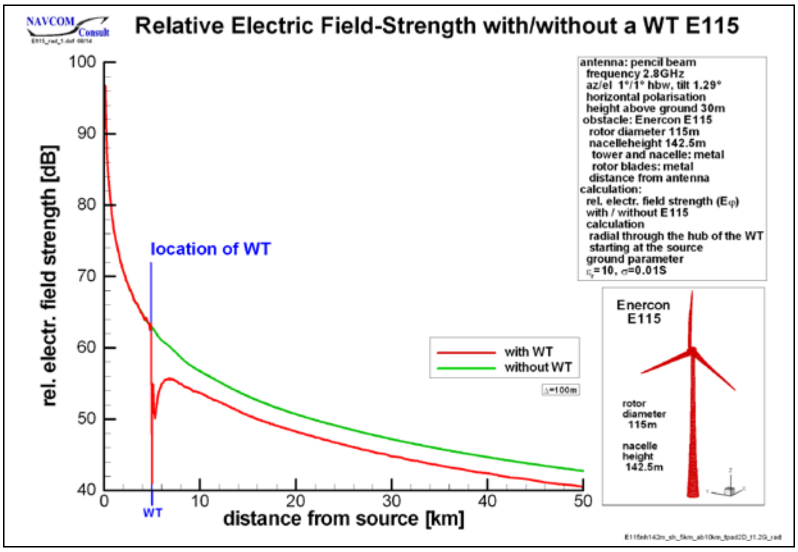

Fig. 6: Radial WR interference effects in front and in the back of a WT; comparison with/without WT

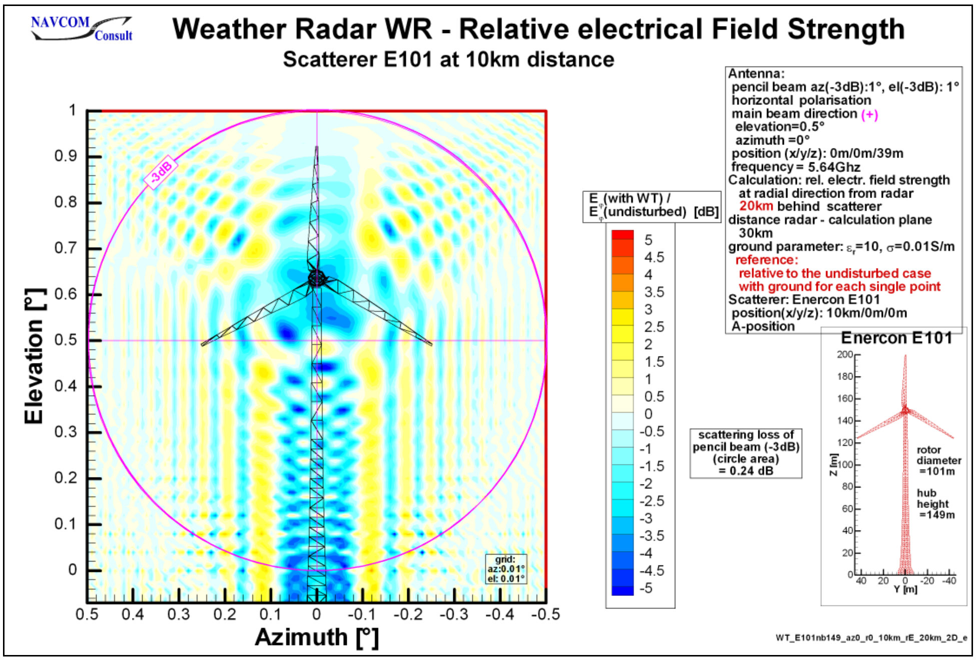

Fig. 7: Detailed interference field 20km in the back of the WT within the -3dB-main-beam of the WR (distance 10km); colour codings ; scaled dimensions for the inserted WT

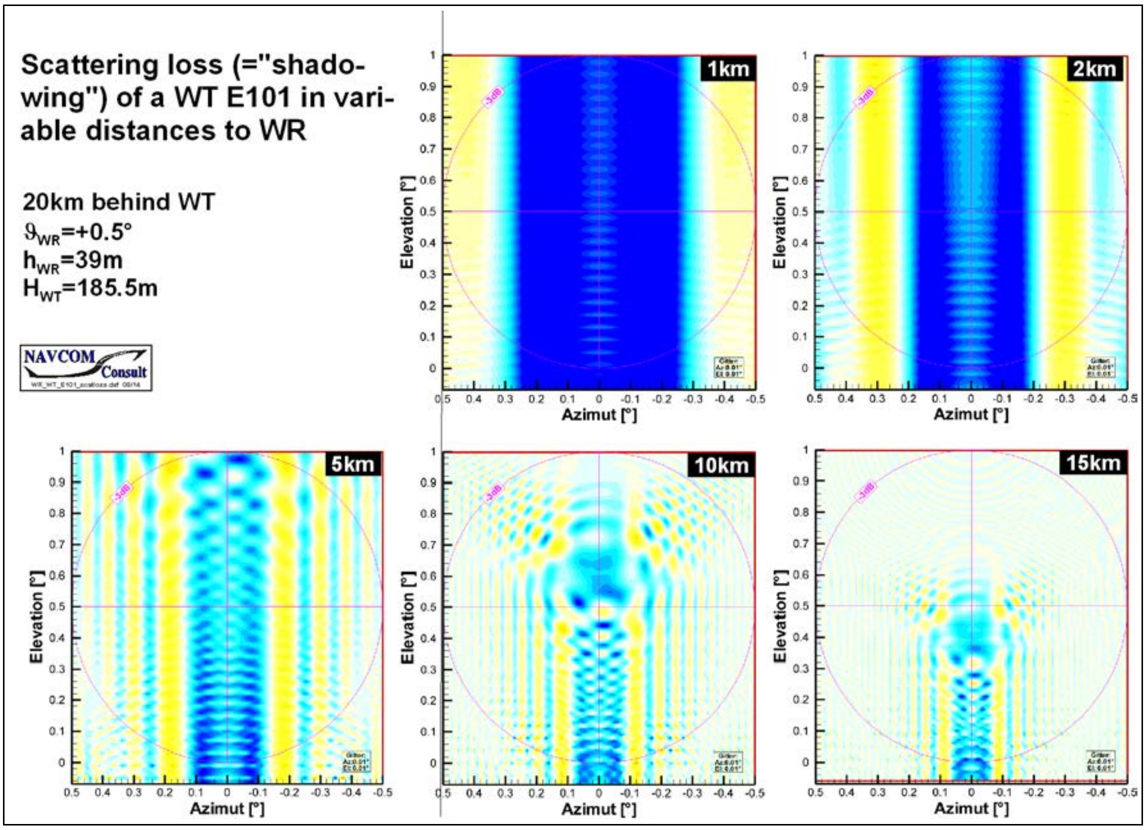

Fig. 8: Detailed interference fields20km in the back of the WT within the -3dB-maim-beam of the WR; variable distances 1km - 15km; colour coding in Fig. 7; blue colour: reduction by scattering; yellow colour: increase by scattering

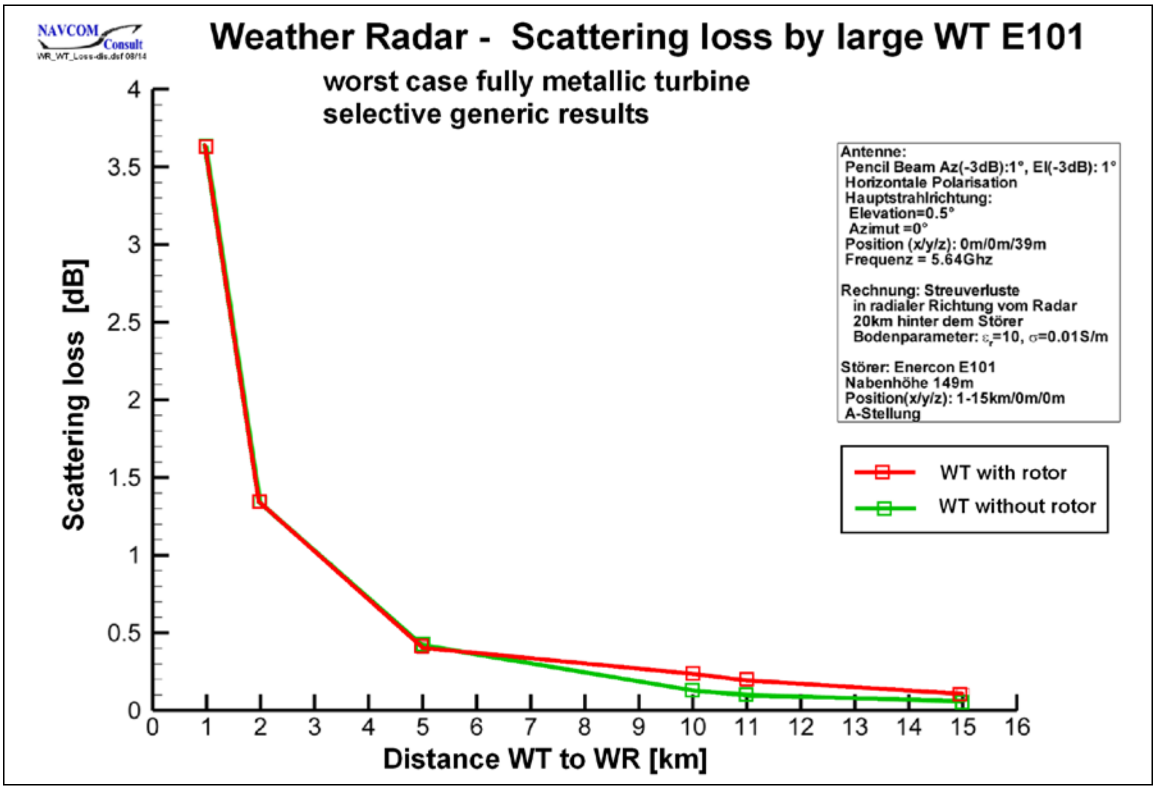

Fig. 9: Scattering loss within the main beam for variable distances between WR and WT; for the smaller distances only the mast is visible for the WR in the lowest beam +0.5° in the given scenario

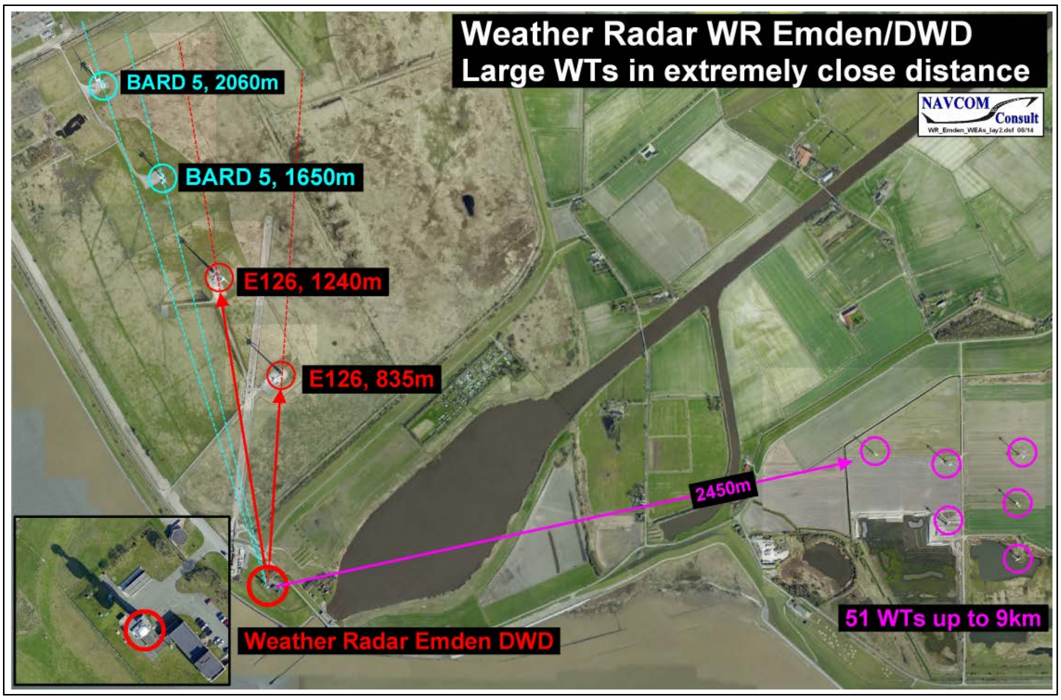

Fig. 10: Very close and very large WTs to a WR (Emden DWD)

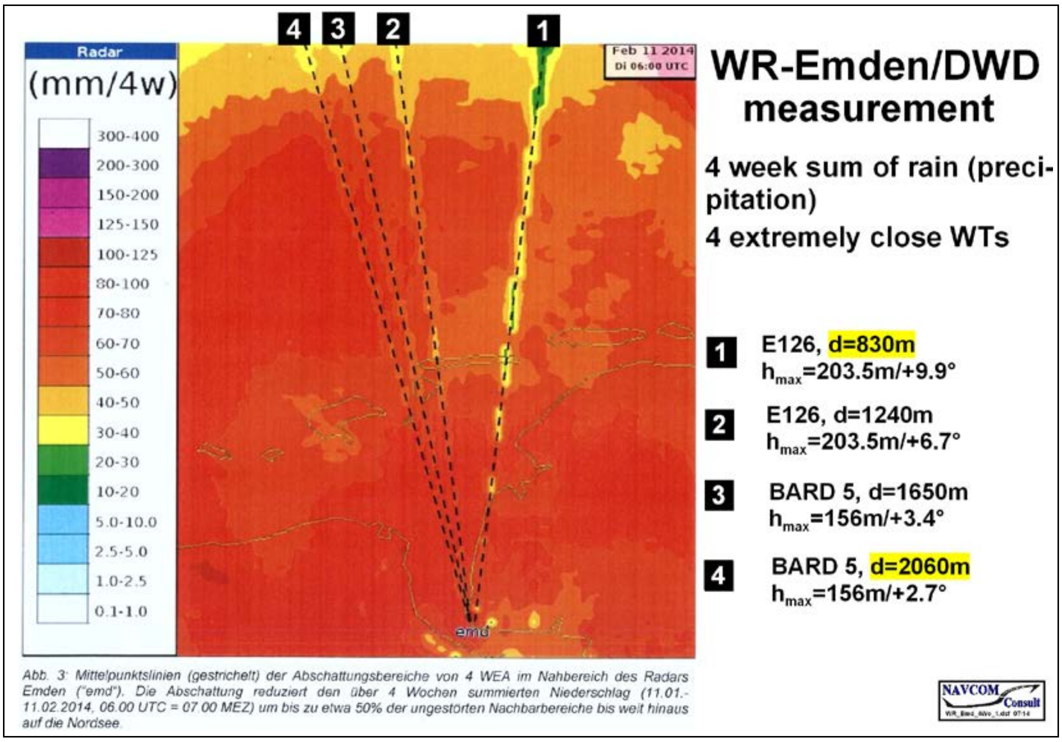

Fig. 11: "Shadowing" effects for the large WTs acc Fig. 11; 4 week rain accumulation (published by DWD)