General Comments

The author explores a simplified technique to estimate the potential impact of wind turbines on weather radar returns, namely reflectivity. More sophisticated optical models are used to validate some of the proposed simplifications.

Outputs from the more sophisticated model are presented as evidence of some assumptions made in the overall simplification. The reflectivity estimates are presented as a measure to estimate the impact of wind farms on weather radars, until such time as signal processing mitigation techniques are available.

Much of the paper focuses on the simplification of the wind turbine/radar interaction. In doing so, the author does make assumptions about wind farm locations and impacts. It is often unclear what reference frame the parameters refer to. Some of the conclusions are based on validation that is difficult to corroborate as little information is provided regarding the optical model simulations, and no real wind turbine data is provided.

However, the exercise is useful in the effort better estimate wind turbine impact for a variety of weather radars, and can likely be extended to other frequencies.

The authors would like to thank the referee for his/her constructive comments to improve the manuscript. We have carefully considered all the comments and revised the manuscript accordingly.

Specific Comments

Abstract

1. Page 1478, Line 4

Replace 'Since nowadays' with 'Current'

The text of the paper has been changed according to the reviewer's comment: "Current signal processing techniques to mitigate Wind Turbine Clutter (WTC) are scarce, so the most practical approach to this issue is the assessment of the potential interference from a wind farm before it is installed."

Section 2

1. Page 1480, First Paragraph

Avoid enclosing statements in parenthesis in the manner used in this paper. Commas should be used instead. The use of parenthesis is colloquial and should be reworded to be more formal.

The text of the paper has been changed according to the reviewer's comment: "These errors may be due to: clutter caused by signal echoes from the wind turbines; signal blockage, as the physical size of the wind turbine creates a shadow zone behind them of diminished detection capacity; and interference to the Doppler mode of the radar, on account of frequency shifted echoes from the rotating blades (Angulo, 2014)"

2. Page 1480, Line 6

Signal blockage is mentioned, but is not discussed in the paper other than the paragraph beginning in Line 20. Mention that this paper does not focus on addressing the signal blockage estimates.

A sentence has been added at the end of the paragraph that begins in Line 20 in order to make clear that this paper does not address the signal blockage estimates: "Consequently, this paper does not focus on addressing the signal blockage estimates."

3. Page 1480, Line 14

Add a sentence or two discussing how the stationary clutter increases the noise floor.

Detection of precipitation requires a signal that exceeds the noise floor by at least the signal to noise ratio. Energy scattered from wind turbines results in the occurrence of increased noise that might cause desired targets to be undetected. Although the signal processing techniques may mitigate the display of false targets generated by the stationary clutter from a wind farm, it will not eliminate effects that raise the noise floor of the radar.

4. Page 1481, Line 19

Replace 'neither' with 'nor'

The text of the paper has been changed according to the reviewer's comment: "The presented method requires neither complex calculations nor the use of a simulation tool, whereas (…)"

Section 3

1. Page 1481, Section 3

Consider moving this section to be the opening statements of Section 4, Methodology, prior to subsection 4.1.

As suggested by the referee, the content of former Section 3 has been included to become the opening statements of the new Section 3, Methodology.

2. Page 1481, Line 26

Remove the statement in the parenthesis.

The statement has been removed from the text.

Section 4.1

1. Page 1482, Line 22

Remove the parenthesis and include the 300 km limit as a normal part of the sentence.

The mentioned parenthesis has been removed: "S-Band is well suited for detecting heavy rain at very long ranges, up to 300 km;".

2. Page 1483, Line 1

The 'less usual' statement seems out of place.

The referred statement has been removed from the text.

3. Page 1483, Line 1

X-band radars, and shorter wavelength radars, are not more sensitive in general. The sensitivity depends on power, directivity, etc. Remove the comment about the sensitivity, as it is unnecessary for the discussion.

The text of the paper has been changed according to the reviewer's comment: "(…) and X-Band weather radars are used only for short range weather observations up to a range of 50 km (ITU-R and WMO, 2008)."

4. Page 1483, -Relative location of weather radar and wind turbine: : :

In some cases, wind farms are located in flat areas, but it is not true for all scenarios. Further, depending on the distance from the radar, contamination from the wind farm can be significant in the antenna sidelobe region, and extend well beyond the lowest elevation angles. Reword this section to indicate that the study is simplifying the scenario, and does not represent every case, but will serve as a proof-of-concept for the model.

The text of the paper has been changed to clarify that the proposed model is based on a representative scenario:

"As a proof-of-concept for the proposed model, a representative scenario has been chosen. This scenario considers that weather radars are usually located in open places that allow unobstructed scanning of a wide area, up to 300 km. Wind farms are also placed on clear areas, where potential wind energy is higher. As weather radar beams use quite directive lobes (usually 1° beam width), wind turbines are illuminated only when radar transmission is pointing to the wind farm. Therefore, the scenario to be analyzed is the potential incidence of the lowest elevation angles of the radar beam on the wind turbines. Lowest elevation angles of the scanning routine are usually transmitted just above horizon, for radar located in flat areas, or slightly below the horizon, for radars located on top of the hills. Accordingly, a reasonable range of the lowest elevation angles where the radar beam can illuminate a wind turbine is -2° to +4° with respect to the horizon (WMO, 2014) (Grande, 2015). The previous assumption leads to incidence angles on the wind turbine nearly perpendicular to the vertical axis of the mast, in particular, within the range 88° < θ < 94°."

Section 4.2.2

2. Page 1484

Consider combining this subsection with the previous, it is very short to be given its own section.

Former Section 4.2.2. has been included as the last paragraph of the previous section, forming a new Section 3.1.1, "Simulation tool and wind turbine models". The change in the order of the subsections is explained later.

3. Page 1484

Add more information about the models. This would be a good place to mention that the model is a tapered cylinder, or a truncated cone. Anything to describe the 'uppermost radius' to the reader would be helpful. Further, it would be useful to know perhaps the kW rating of the turbine for reference.

According to the referee's comments, more information about the wind turbine models and a note about the actual geometry of the mast have been included in the text. Moreover, the rated power of the wind turbine models to be analyzed has been included in Table 1. The first three paragraphs of the resulting new Section 3.1.1, "Simulation tool and wind turbine models", are as follows:

"The present study is based on the accurate assessment of RCS values of wind turbines by applying the Physical Optics (PO) theory. More precisely, the software tool POfacets (Jenn, 2005) has been used to calculate RCS patterns of three different wind turbine models. To do so, detailed facets-based representations of these wind turbine models have been prepared for the application of numerical solutions of the PO method for RCS estimations. More in depth descriptions of the Physical Optics Method and the simulation tool can be found in (Jenn, 2005), (Grande, 2014), (Grande, 2015).

It should be noted that this tool provides accurate RCS values for a specific rotor orientation and blade position, but at the expense of having to design rigorous representations of the wind turbine models. Hence, estimations of RCS values for each specific position of the blades must be conducted, and therefore, hundreds of RCS simulations are required in order to obtain a detailed characterization of the RCS patterns for different working conditions. The analysis of this huge set of RCS values is the basis of the proposed simplified model to be integrated in the prediction tools for potential interference from a wind farm. In fact, the main motivation of the proposed simplified model is precisely avoiding the need of such a simulation effort in future cases under study.

As previously mentioned, three commercial wind turbine models were chosen for the analysis, which constitutes a representative selection of the wind turbines that are currently installed. Typical horizontal-axis wind turbines are composed of a mast or supporting tower, commonly made from tubular steel; a nacelle that holds all the turbine machinery and rotates to follow the wind direction; and a rotor with three blades of complex aerodynamic surface, being the rotor shaft tilted above the horizontal to enable greater clearance between the blades and the *mast. Characteristics of the selected models are summarized in Table 1. It should be noted that upper and lower radii of the masts are different because the geometry of the supporting tower of the wind turbines is not a perfect right circular cylinder but a tapered cylinder."*

Section 4.2.3

1. Page 1484

Accuracy is not the correct term to use. Use 'Precision' or 'Quantization' in the subsection title. Accuracy would refer to actual wind turbine RCS measurements to corroborate the model.

As suggested by the reviewer, the term accuracy has been replaced by precision in the subsection title.

2. Page 1484, Line 23-24

It is not apparent to the reader what the theta and phi parameters represent exactly. It should be clear in Figure 1 what phi represents, and that it is referenced to the normal of the blade face and toward the radar along the radar line of sight (I think?). It would also be useful to define a parameter for the blade rotation plane, again with explicit descriptions so the reader can visualize easily.

In order to make the coordinate system clearer, Fig. 1 has been simplified. Moreover, theta and phi parameters have been explained in Section 3.1.1, "Simulation tool and wind turbine models", which was Section 3.2.1 before but has been moved to the beginning of Section 3 in order to clarify the coordinate system before explaining the considerations of the analysis (now in Section 3.2).

The last paragraph of Section 3.1.1 is now as follows:

"Fig. 1 shows the reference coordinate system for the analysis. The wind turbine rotor is supposed to be oriented towards the x-axis and R *refers to the radar position. As shown in the figure, θ is the angle from the zenith that defines the radar position in the vertical plane, and Φ specifies the horizontal position of the radar with respect to the rotor orientation, i.e., with respect to the rotor shaft axis "*

Section 5

1. Page 1485, Line 19

This is the first mention of the slant surface. A drawing or more discussion about the model (Section 3) should be included.

As explained in Comment 3 referring to former Section 4.2.2, a note about the actual geometry of the mast has been including in the text, in the new Section 3.1.1.

2. Page 1486, Line 5

When the blades are in a vertical position, shouldn't the maximal return be at 90 degrees? Or is there a slant angle to the blades as well? This should be discussed more in the description of the wind turbine model (Section 3).

As suggested by the reviewer and detailed in the response to Comment 3 referring to former Section 4.2.2., a more detailed description of the wind turbine models has been included in Section 3.1.1. This description includes a comment about the aerodynamic design of the blades, which scatters incident energy in multiple directions, and the fact that the rotor shaft is tilted above the horizontal, which further complicates the a priori estimation of the direction of the maximum scattering from the blades.

Section 6.1

1. Page 1487, Line 8

Remove the term 'really'.

The term "really" has been removed from the text: "(…) the half cone angle α that defines the slant surface of the mast is small (see Figure 7),"

Section 6.3

1. Whole section

Some effort is spent in validating the simplified model against the optical model, but no effort is spent in validating the reflectivity calculation. It would greatly strengthen the work if the estimates for wind turbine reflectivity could be corroborated with real data, particularly the Doppler or blade reflectivity estimate.

The authors fully agree with the referee on the value of comparing the results of the model with real data. Unfortunately, such data are not available for the authors. Even though the proposed model cannot be validated against real reflectivity values, the authors think that the model provides a practical and easy-to-apply estimation of reflectivity values from wind turbines that may be of interest in order to avoid interference effects of wind farms on weather radars.

Section 7

1. Page 1494

It is not clear how the reflectivity values will be used. Please be explicit to the reader in how this model will aid in the planning for wind turbine clutter impact. Specifically, address the two issues mentioned at the beginning of the paper, clutter and Doppler, and how this technique can help plan for impact assessments.

According to the referee's comments, additional discussion has been included in Section 6 (former Section 7):

"The proposed RCS model can be used to estimate the maximum clutter due to the presence of a wind turbine, estimating the scattered power from the mast. On the other hand, even if the

Doppler radar under study uses a clutter filter that suppresses stationary objects, the rotating blades of a wind turbine might still be detected. As proved in (Norin, 2015), weather information from radar cells affected by a wind turbine is not always lost. In fact, when precipitation gives rise to reflectivity values stronger than those due to wind turbines, radar data could still be used. Therefore, the reflectivity model proposed in this paper is of interest not only to assess a potential detrimental impact on the performance of a weather radar, but also to evaluate to which extent this degradation might exist, if reflectivity values from precipitation and wind turbine blades are compared."

Estimating Reflectivity Values from Wind Turbines for Analyzing the Potential Impact on Weather Radar Services

I. Angulo[1], O. Grande[1], D. Jenn[2], D. Guerra[1], D. de la Vega[1]

[1] {University of the Basque Country (UPV/EHU), Bilbao, Spain}

[2] {Naval Postgraduate School, Monterey, USA}

Correspondence to: D. de la Vega (david.delavega@ehu.es)

Abstract

The World Meteorological Organization (WMO) has repeatedly expressed concern over the increasing number of impact cases of wind turbine farms on weather radars. Since nowadaysCurrent signal processing techniques to mitigate Wind Turbine Clutter (WTC) are scarce, so the most practical approach to this issue is the assessment of the potential interference from a wind farm before it is installed. To do so, and in order to obtain a WTC reflectivity model, it is crucial to estimate the Radar Cross Section (RCS) of the wind turbines to be built, which represents the power percentage of the radar signal that is backscattered to the radar receiver.

This paper first characterizes the RCS of wind turbines in the weather radar frequency bands by means of computer simulations based on the Physical Optics theory, and then proposes a simplified model to estimate wind turbine RCS values. This model is of great help in the evaluation of the potential impact of a certain wind farm on the weather radar operation.

1 Introduction

The potential impact of wind turbines on weather radar performance has been extensively studied in the last few years, with several evidences of wind turbine clutter observations in meteorological radar applications (Isom, 2008), (Gallardo, 2011), (Norin, 2012), (Vogt, 2011) (WMO, 2005, 2010). The main objective of these studies is to characterize and try to mitigate the so-called Wind Turbine Clutter (WTC), mainly by means of digital signal processing such as clutter-filtering techniques.

Unfortunately, these solutions are not widely available yet. Meanwhile, the most practical approach to this issue is the prediction of the potential impact on a certain weather radar service before installing a wind farm. In most cases, the identification of a potential impact allows the planning of alternative solutions in order to guarantee the coexistence of wind energy and meteorological radar services.

Wind Turbine Clutter reflectivity depends on many factors including wind turbine dimensions, wind direction and velocity, angle of incidence and radar frequency. In order to measure how efficiently radar pulses are backscattered by wind turbines, existing models of wind turbine clutter and weather radar recommendations rely on the turbines' Radar Cross Section (Tristant, 2006), (ITU-R, 2009), (Norin, 2012) . The RCS is the projected area required to intercept and isotropically radiate the same power as the target scatters toward the receiver, and thus it is normally expressed in dB with respect to a square meter (dBsm) (Skolnik, 2008) (Rinehart, 1997).

In this context, the goal of this paper is to propose simplified formulae for the estimation of reflectivity values from wind turbines at frequencies used by weather radars. These formulae aim at being easily implementable in software tools for estimating the potential impact of wind farms on weather radars.

For this purpose, first RCS patterns for different working conditions of the wind turbines are obtained by means of Physical Optics simulations, and subsequently analyzed. Additionally, separate RCS patterns of the parts of the turbine are also calculated, in order to compare the relative contribution of each component. Based on these simulations, a simple algorithm to evaluate the potential impact of a wind farm on a nearby weather radar is proposed.

It should be mentioned that similar studies for characterizing RCS of wind turbines have been carried out for evaluating the impact on different services such as maritime radars (Grande, 2014) or television (Angulo, 2011). However, as scattering is very dependent on working frequency and illumination conditions, results cannot be extrapolated. Moreover, preliminary results of the analysis presented in this paper are included in a previous communication from the authors (Grande, 2015). Those results correspond to a single wind turbine model and a single working frequency. In the present paper, results are extended to three wind turbine models of different size and the three frequency bands assigned to weather radar services;

besides, based on the obtained results, a novel formulation for estimating the WTC reflectivity values for weather radar applications is proposed. This work aims at making impact studies for the prediction of potential interferences between weather radar services and wind farm deployments easier to conduct.

2 Impact of wind farms on weather radars

In weather radars, wind turbines may lead to misidentification of precipitation features and to erroneous characterization of meteorological phenomena. These errors may be due to: clutter (caused by signal echoes from the wind turbines);, signal blockage, (as the physical size of the wind turbine creates a shadow zone behind them of diminished detection capacity) ; and interference to the Doppler mode of the radar, on account of (frequency shifted echoes from the rotating blades) (Angulo, 2014).

The clutter from wind turbines is due to radar echoes coming from a turbine and reaching the radar with a power level higher than the radar detection threshold, preventing from correctly detecting the precipitation level in the affected area. Although most of current radars include signal processing techniques that remove static scattering from turbine masts, the scattered energy will increase the effective noise floor of the radar receiver, which degrades the detection capacity, and therefore, the data quality obtained by the radar. Detection of precipitation requires a signal that exceeds the noise floor by at least the signal to noise ratio. Energy scattered from wind turbines results in the occurrence of increased noise that might cause desired targets to be undetected. Although the signal processing techniques may mitigate the display of false targets generated by the stationary clutter from a wind farm, it will not eliminate effects that raise the noise floor of the radar (Tristant, 2006) (Lemmon, 2008).

Regarding the Doppler mode of the radar, as it is aimed at detecting moving targets, in order to determine the influence of a wind turbine on this operation mode only the scattering from the blades should be considered.

Therefore, both the clutter phenomenon and the interference to the Doppler mode depend on the scattering characteristics of wind turbines. By contrast, as the blocking of the radar beam is due to the physical obstruction of the radar beam by the wind turbine, the methodology to estimate a potential impact of a wind farm due to signal blockage is not related to the RCS of wind turbines but to the percentage of the beam section blocked by the wind turbine structure (Tristant, 2006). Consequently, this paper does not focus on addressing the signal blockage estimates.

As the RCS of a wind turbine depends both on fixed parameters (such as the dimensions and materials of each component of the wind turbine) and on variable parameters (such as position of the rotating blades and rotor orientation with respect to the radar), RCS values may vary drastically according to wind turbine working regimes and illumination conditions.

The calculation of RCS values by conventional prediction methods, such as the method of moments (MoM) or the finite difference time domain (FDTD) method, provides accurate results, but rely upon extremely detailed representations of the turbine, which requires significant modeling and complex calculations with great computational effort. Consequently, these RCS prediction methods cannot be easily implemented in computer simulation tools for analyzing the potential impact of a specific wind farm.

On the contrary, and due to the absence of simplified formulation, some published guidelines for analyzing the impact of wind turbines on radar services use typical fixed RCS values, disregarding the particular features of each installation (ITU-R M.1849, 2009), (Tristant, 2006). This is a very simple way to deal with wind turbine scattering, but its main disadvantage is that the proposed RCS values do not take into account the characteristics of the real scenario under analysis: wind turbine dimensions, angle of incidence and working frequency, amongst others. As a result, these proposed typical constant RCS values may lead to important estimation errors.

In this paper, a simplified formulation for determining accurate WTC reflectivity values is proposed. The presented method ~~does not~~ requires neither complex calculations ~~neither~~ nor the use of a simulation tool, whereas it provides RCS values adapted to the particular features of the case under analysis: dimensions of the wind turbine models, illumination conditions and working frequency.

~~3 Objectives~~

~~The main objective of this paper is to develop an estimation model of wind turbine reflectivity values for weather radars, consisting in a simplified formulation, easy to apply in the~~

development of the impact studies, without requiring a complex software tool or a high amount of resources (high computational load or computation time).

The estimation model should fulfill the following conditions:

- Despite being a simplified formulation, the model should provide accurate Radar Cross Section values, which are directly translated into reflectivity values.
- The model should consider the variability of the RCS values, generated by the rotor orientation and the blades rotation, as the RCS values are very dependent on the specific relative positions of the different components of the turbine with respect to the radar.
- The model should be applicable to turbine models of different size, different working frequencies and different radar illumination conditions.

3 Methodology

The main objective of this paper is to develop an estimation model of wind turbine reflectivity values for weather radars, consisting in a simplified formulation, easy to apply in the development of the impact studies, without requiring a complex software tool or a high amount of resources.

The estimation model should fulfill the following conditions:

- Despite being a simplified formulation, the model should provide accurate Radar Cross Section values, which are directly translated into reflectivity values.
- The model should consider the variability of the RCS values, generated by the rotor orientation and the blades rotation, as the RCS values are very dependent on the specific relative positions of the different components of the turbine with respect to the radar.
- The model should be applicable to turbine models of different size, different working frequencies and different radar illumination conditions.

3.1 Simulation conditions

3.1.1 Simulation tool and wind turbine models

The present study is based on the accurate assessment of RCS values of wind turbines by applying the Physical Optics (PO) theory. More precisely, the software tool POfacets (Jenn, 2005) has been used to calculate RCS patterns of three different wind turbine models. To do so, detailed facets-based representations of these wind turbine models have been prepared for the application of numerical solutions of the PO method for RCS estimations. More in depth descriptions of the Physical Optics Method and the simulation tool can be found in (Jenn, 2005), (Grande, 2014), (Grande, 2015).

It should be noted that this tool provides accurate RCS values for a specific rotor orientation and blade position, but at the expense of having to design rigorous representations of the wind turbine models. Hence, estimations of RCS values for each specific position of the blades must be conducted, and therefore, hundreds of RCS simulations are required in order to obtain a detailed characterization of the RCS patterns for different working conditions. The analysis of this huge set of RCS values is the basis of the proposed simplified model to be integrated in the prediction tools for potential interference from a wind farm. In fact, the main motivation of the proposed simplified model is precisely avoiding the need of such a simulation effort in future cases under study.

As previously mentioned, three commercial wind turbine models were chosen for the analysis, which constitutes a representative selection of the wind turbines that are currently installed. Typical horizontal-axis wind turbines are composed of a mast or supporting tower, commonly made from tubular steel; a nacelle that holds all the turbine machinery and rotates to follow the wind direction; and a rotor with three blades of complex aerodynamic surface, being the rotor shaft tilted above the horizontal to enable greater clearance between the blades and the mast. Characteristics of the selected models are summarized in Table 1. It should be noted that upper and lower radii of the masts are different because the geometry of the supporting tower of the wind turbines is not a perfect right circular cylinder but a tapered cylinder.

Fig. 1 shows the reference coordinate system for the analysis. The wind turbine rotor is supposed to be oriented towards the x-axis and *R* refers to the radar position. As shown in the figure, θ is the angle from the zenith that defines the radar position in the vertical plane, and

Φ specifies the horizontal position of the radar with respect to the rotor orientation, i.e., with respect to the rotor shaft axis.

3.1.2 Simulation precision

The analysis is based on the assessment of backscattering patterns for a set of elevation angles (variation in *θ*), and different conditions of rotor orientation with respect to the radar (variation in *Φ*) and blades position (rotating blades).

Calculations with particularly high resolution have been conducted for RCS vertical patterns (resolution of 0.001° in *θ*), as great variability is expected in this plane. The effect of the rotating blades has been analyzed by simulations with a difference of 15º in the rotation angle of the blades. In addition, these estimated RCS values have been obtained for different positions of the rotor with respect to the incident signal in the horizontal plane (aspect angles separated 1° in *Φ*).

In order to evaluate the relative significance of the signal backscattered by the different parts of the wind turbine, separated RCS patterns of the mast, nacelle and single blades have been obtained and compared with the RCS pattern of the whole wind turbine.

~~3.1~~3.2 Considerations of the analysis

The case under analysis is a wind farm located within the detection volume of a weather radar. When this situation occurs, some specific conditions are applicable. The thorough outline of these conditions allows the clear delimitation of the scenario under analysis:

- **Monostatic backscattering**. Weather radars only receive monostatic backscattered signals, so monostatic RCS values are analyzed in this paper.

- **Frequency bands**. The analysis is conducted for the frequency bands assigned to weather radar operation: 2700-2900 MHz in S band; 5250-5725 MHz (mainly 5600-5650 MHz) in C band; and 9300-9500 GHz in X band (ITU-R, 2008). In weather radars, S-Band is well suited for detecting heavy rain at very long ranges~~,~~ ~~(~~up to 300 km~~)~~; C-Band represents a good compromise between range and reflectivity and cost, and they can provided rain detection up to a range of 200 km; and ~~less usual~~ X-

Band weather radars ~~are more sensitive, and they~~ are used only for short range weather observations up to a range of 50 km (ITU-R and WMO, 2008).

- **Materials**. The metallic mast can be considered as perfect electric conductor (PEC). Although modern blades are made of composite materials which are difficult to characterize, in the simulations, blades are supposed to be metallic, in order to consider the worst-case assumption for this component of the turbine.
- **Relative location of weather radar and wind turbine, and elevation angles**. As a proof-of-concept for the proposed model, a representative scenario has been chosen. This scenario considers that w~~W~~eather radars are usually located in open places that allow unobstructed scanning of a wide area, ~~– (~~up to 300 km~~)~~. Wind farms are also placed on clear areas, where potential wind energy is higher. As weather radar beams use quite directive lobes (usually 1° beam width), wind turbines are illuminated only when radar transmission is pointing to the wind farm. Therefore, the scenario that must be analyzed is the potential incidence of the lowest elevation angles of the radar beam on the wind turbines. Lowest elevation angles of the scanning routine are usually transmitted just above horizon, for radar located in flat areas, or slightly below the horizon, for radars located on top of the hills. Accordingly, a reasonable range of the lowest elevation angles where the radar beam can illuminate a wind turbine is -2° to +4° with respect to the horizon (WMO, 2014) (Grande, 2015). The previous assumption leads to incidence angles on the wind turbine nearly perpendicular to the vertical axis of the mast, in particular, within the range 88° < θ < 94°~~(where θ is the angle from the zenith, see Fig. 1 for reference coordinate system)~~.

~~3.2 Simulation conditions~~

~~3.2.1 Simulation tool~~

~~The present study is based on the accurate assessment of RCS values of wind turbines by applying the Physical Optics (PO) theory. More precisely, the software tool POfacets (Jenn, 2005) has been used to calculate RCS patterns of three different wind turbine models, specified in Sect. 4.2.2. To do so, detailed facets-based representations of these wind turbine models have been prepared for the application of numerical solutions of the PO method for RCS estimations. More in depth descriptions of the Physical Optics Method and the simulation tool can be found in (Jenn, 2005), (Grande, 2014), (Grande, 2015).~~

~~It should be noted that this tool provides accurate RCS values for a specific rotor orientation and blade position, but at the expense of having to design rigorous representations of the wind turbine models. Hence, estimations of RCS values for each specific position of the blades must be conducted, and therefore, hundreds of RCS simulations are required in order to obtain a detailed characterization of the RCS patterns for different working conditions. The analysis of this huge set of RCS values is the basis of the proposed simplified model to be integrated in the prediction tools for potential interference from a wind farm. In fact, the main motivation of the proposed simplified model is precisely avoiding the need of such a simulation effort in future cases under study.~~

~~, three commercial wind turbine models, which constitute a representative selection of the wind turbines that are currently installed, were chosen for the analysis. Dimensions of the selected models are summarized in Table 1.~~

~~3.2.2 Simulation accuracy~~

~~The analysis is based on the assessment of backscattering patterns for the previously defined set of elevation angles (variation in θ), and different conditions of rotor orientation (variation in Φ) and blades position (rotating blades).~~

~~Calculations with particularly high resolution have been conducted for RCS vertical patterns (resolution of 0.001° in θ), as great variability is expected in this plane. The effect of the rotating blades has been analyzed by simulations with a difference of 15° in the rotation angle of the blades. In addition, these estimated RCS values have been obtained for different positions of the rotor with respect to the incident signal in the horizontal plane (aspect angles separated 1° in Φ).~~

~~In order to evaluate the relative significance of the signal backscattered by the different parts of the wind turbine, separated RCS patterns of the mast, nacelle and single blades have been obtained and compared with the RCS pattern of the whole wind turbine.~~

4 Simulation results and analysis

As previously mentioned, simulations have been carried out for three frequencies representative of the different weather radar frequency bands (2.80 GHz, 5.65 GHz and 9.40 GHz), and three wind turbine models based on actual commercial turbines.

As an example, Fig. 2 to Fig. 4 show the vertical variation of the RCS patterns of wind turbine models 1 to 3 for a specific rotor orientation for the three frequencies under analysis. It can be observed that the RCS patterns show great variability, and a very directive main lobe is noticeable in all cases.

This maximum value of the RCS corresponds to an illumination direction of θ = 89.56° with respect to the zenith in case of WT Model 1, θ = 89.48° in case of WT Model 2, and θ = 89.42° for WT Model 3. Taking into account the slant surface of the masts, these directions correspond to the direction normal to the mast surface of each wind turbine model. As expected, the maximum RCS value is larger for the tallest wind turbine. Moreover, when comparing Fig. 2 to Fig. 4, it is clearly observed that the main lobe is both higher and narrower as the frequency increases. This maximum value of the RCS in the vertical pattern is maintained for all the azimuth values due to the symmetry of the mast in the horizontal plane.

In order to identify the contribution of the blades and nacelle, for the highest frequency and a specific rotor orientation, the RCS of WT Model 3 is depicted in Fig. 5 for different positions of the blades (every 30° in the rotation movement). The RCS pattern of the isolated mast is also depicted in Fig. 5. As observed in the figure, whereas the contribution from the blades varies in amplitude and position with the rotation movement, the maximum RCS of the wind turbine is constant and it is clearly generated by the mast. Fig. 5 also shows that the main contribution from the rotor is due to a blade being in vertical position (see curves related to P000 and P060 in Fig. 5).

Obviously, the contribution from the blades is strongly dependent on the rotor orientation with respect to the incident radar signal, whereas the contribution from the mast remains invariable in the horizontal plane due to its symmetry with respect to the vertical axis of the mast. This statement is confirmed by Fig. 6, where the vertical RCS patterns of WT Model 2 are compared for different illumination directions in the horizontal plane (different Φ values).

A first important conclusion obtained from the extensive set of simulations carried out is that the main scatterer of the wind turbine for the different frequency bands used for weather radar is the supporting mast. Moreover, the main feature of the scattering pattern of the mast is a main lobe normal to the slant surface, extremely directive in the vertical plane and omnidirectional in the horizontal plane. The blades, by contrast, provide variable levels of signal scattering depending on the rotor orientation and blade positions, always significantly lower than the amplitude of the main lobe from the mast.

The clear characterization of the scattering from the mast, in contrast with the variable scattering from the rotating blades, is the basis of the proposed model for calculating the wind turbine RCS values, which will differentiate scattering from fixed and moving parts of the turbine.

5 Proposed model

5.1 Scattering from the mast

As demonstrated in the previous section, the mast is the main scatterer of the wind turbine due to its large dimensions, as it generates the maximum value of the RCS pattern.

The geometry of the mast can be approximated by a right cylinder, as for commercial wind turbine models, the half cone angle α that defines the slant surface of the mast is ~~really~~ small (see Figure 7),

$$\alpha = \tan^{-1}\left(\frac{r_2 - r_1}{H}\right). \quad (1)$$

For example, for the three models under analysis, the half cone angle is smaller than 0.6º. Therefore, a perfectly conducting right cylinder tilted at an angle α is used to assess the backscattered RCS of the mast based on the PO theory.

In (Siegel, 1955) the RCS pattern of an elliptic cylinder is obtained as a function of its dimensions and the angular positions of the transmitter and receiver in both the vertical and the horizontal planes. As for radar applications only backscattering is of interest, the formulae in (Siegel, 1955) for a circular cylinder can be simplified and expressed as:

$$\sigma_{cylinder} = \frac{2\pi}{\lambda} r L^2 \sin\theta \left(\frac{\sin\left(\frac{2\pi}{\lambda} L \cos\theta\right)}{\frac{2\pi}{\lambda} L \cos\theta}\right)^2 \quad (2)$$

where λ is the wavelength of the radar transmission, θ is the aspect angle as defined in Figure 7, r is the cylinder radius and L is the cylinder height.

In order to adapt the previous expression to the actual geometry of the mast, two approximations are considered:

1.- In (Skolnik, 2008), it is stated that Eq. (2) may be used to estimate the RCS of a truncated right circular cone if the radius r is replaced by the mean radius of the cone and L is replaced by the length of the slanted surface.

2.- Taking into account the results of the previous section, it is clear that the backscattering pattern of the mast is extremely directive in the direction perpendicular to the slanted surface of the mast. Therefore, Eq. (2) should be slightly modified in order to account for the half cone angle α.

According to the above mentioned considerations, the proposed model to calculate the RCS of the wind turbine mast is given by

$$\sigma_{mast} = \frac{2\pi}{\lambda} r L^2 \sin(\theta + \alpha) \left(\frac{\sin\left(\frac{2\pi}{\lambda} L \cos(\theta+\alpha)\right)}{\frac{2\pi}{\lambda} L \cos(\theta+\alpha)} \right)^2, \quad (3)$$

where λ is the wavelength of the radar transmission, θ is the aspect angle as defined in Figure 7, α is the half cone angle as given by Eq. (1), r is the mean radius of the truncated cone

$$r = \frac{r_1 + r_2}{2}, \quad (4)$$

and L is the length of the slanted surface of the mast

$$L = \frac{H}{\cos\alpha}. \quad (5)$$

In order to prove the validity of the proposed model, the obtained results are compared to the simulation values presented in the previous section. For all the analyzed cases (three wind turbine models, three working frequencies) the mean error between the simulation values and the values obtained according to Eq. (3) is lower than 0.85 dB. An example to demonstrate that simulation and modeling values are very well aligned is shown in Fig. 8.

5.2 Scattering from the blades

From the results of simulations of the RCS patterns, it is clearly shown that the scattering from the blades is significantly lower than the scattering from the mast. Moreover, it should be considered that, as demonstrated in the simulations, the scattering from the blades is strongly dependent on the position of the rotor with respect to the radar. In order to analyze a potential impact situation, therefore, a detailed representation of the blades and all the possible movements of the wind turbine should be needed. However, obtaining detailed representations of actual wind turbine blades is quite difficult, as the blade design is property of the wind turbine manufacturer, and the analysis of hundreds of different combinations of rotor orientation and blades position requires a huge amount of time and effort.

A simpler approach to this issue is considering a maximum value of the scattering from the blades. Therefore, instead of a complete scattering model from the blades, the objective of this section is to characterize the maximum RCS value due to the blades for each wind turbine model. In fact, as commented before and shown in Fig. 5, the maximum RCS due to the blades corresponds to the contribution of a single blade in vertical position.

From the set of simulations carried out in this analysis, the maximum RCS values from the mast and blades are shown in Table 2. Obviously, these maximum RCS values are frequency dependent. However, if the relation between the maximum RCS from the mast and the maximum RCS from the blades is obtained, it can be observed that this relation remains almost constant for the different frequency bands.

Although their complex geometry prevents from obtaining simple RCS models to characterize the scattering from the blades, the relation between the maximum RCS from the mast and the maximum RCS from the blades must be proportional to their corresponding dimensions.

As a very simple approach, the blade can be represented by a triangle. Considering the twist angle of the blades, this triangle will be never completely facing the radar. As a rough approach, we will consider that only the 50% of the wind turbine blade will be directly illuminated by the radar. Therefore, the relative scattering area from the blades A_{blades} is calculated as:

$$A_{blades} = 0.5\frac{w \cdot l}{2}, \quad (6)$$

where w is the maximum blade width and l is the blade length.

The mast, by contrast, will be constantly facing the radar with an area that can be approximated by a trapezoid:

$$A_{mast} = (r_1 + r_2)H, \quad (7)$$

Where r_1 and r_2 are the upper and lower radii of the mast, and H is the mast height.

Thus, the relation Δ in dB between the relative scattering area of the mast and blades can be obtained as:

$$\Delta = 10\log_{10}\left(\frac{4H(r_1+r_2)}{w \cdot l}\right). \quad (8)$$

According to the wind turbine characteristics gathered in Table 1, these relations are calculated and shown in Table 3. If values in Table 2 and Table 3 are compared, it can be stated that the relation in dB between the relative scattering area of the mast and blades can be considered a good approximation of the difference in dB between the maximum RCS from the mast and the maximum RCS from the blades. Taking this into account, the maximum RCS from the blades (dBsm) can be obtained as:

$$\sigma_{blades} = \max \ \{\sigma_{mast}\} - \Delta = 10\log_{10}\left(\frac{2\pi}{\lambda} r L^2\right) - 10\log_{10}\left(\frac{4H(r_1+r_2)}{w \cdot l}\right). \quad (9)$$

5.3 Converting RCS values to WTC reflectivity values

In order to model wind turbine clutter, the RCS of a wind turbine must be converted to the equivalent radar reflectivity factor.

The weather radar equation, for distributed targets such as rain, is given by

$$P_r = \frac{P_t G^2 \theta_0 \Phi_0 c \tau \pi^3 |K|^2 z}{1024 \ln(2) \lambda^2 R^2}, \quad (10)$$

where P_r is the power received back by radar, P_t is the power transmitted by radar, θ_0 and Φ_0 are the elevation and azimuth beamwidths, c is the speed of light, τ is the radar pulse length, $|K|^2$ is the complex index of refraction of the hydrometeor, λ is the wavelength of the radar pulse, R is the distance to the target and z is the radar reflectivity factor (ITU-R, 2009), (Rinehart, 1997), (Norin, 2012). The radar reflectivity factor z, normally expressed in decibels of reflectivity (dBZ), is the quantity that is used to obtain the rain rate:

$$z = \frac{P_r 1024 \ln(2) \lambda^2 R^2}{P_t G^2 \theta_0 \Phi_0 c \tau \pi^3 |K|^2}. \quad (11)$$

On the other hand, the radar equation for a point target, such as distant wind turbine contained within a range resolution cell, is given by

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{64 \pi^3 R^4}, \quad (12)$$

where σ is the RCS of the wind turbine (Knott, 2006).

Assuming that the wind turbine is entirely included within the beam cell resolution of the weather radar, we can compare equations (10) and (12) and then obtain the radar reflectivity factor as

$$z = C_1 \frac{\sigma}{R^2}, \quad (13)$$

where C_1 is a constant that depends on the parameters of the radar system:

$$C_1 = \frac{16\ln(2)}{\pi^6 c} \cdot \frac{\lambda^4}{\theta_0 \Phi_0 \tau} \cdot \frac{1}{|K|^2}. \quad (14)$$

5.4 Complete model for estimating WTC reflectivity in weather radar bands

Results obtained in the previous subsections are the basis of the complete model to characterize the signal scattering from wind turbines in the weather radar bands proposed in this paper. This simplified model for estimating WTC reflectivity in weather radar bands is summarized in Table 4.

First, based on the specific characteristics of the wind turbine and the working frequency, the RCS pattern of the mast near the direction normal to the slant surface is obtained. The RCS from the mast is used to determine the main lobe of the RCS pattern of the whole wind turbine.

Then, the maximum RCS value from the blades is calculated, as the maximum RCS value of the mast minus the relation in dB between the relative scattering areas of the mast and blades. This maximum RCS value from the blades establishes an upper bound, in such a way that all the possible orientations of the nacelle and blades are considered.

In order to combine both patterns and obtain the simplified RCS pattern of the whole wind turbine, the RCS values from the mast are used for angles θ near the incidence normal to the slanted surface of the mast, i.e. for θ values such that $\sigma_{mast} \geq \sigma_{blades}$. This way, the main lobe of the RCS pattern of the whole wind turbine is estimated. For incidence angles off the main lobe due to the mast, and up to the limiting angles θ due to the illumination characteristics of weather radars, the maximum RCS value from the blades is applied.

An example of the results of this proposed RCS model is shown in Fig. 9, together with the simulated results of the RCS pattern for different rotor orientations. In the figure, it can be seen that the maximum RCS of the mast is well approximated by the model, and the mask established off the main lobe covers the scattering from the blades for different rotor orientations.

Once the RCS pattern is obtained, for a specific illumination condition and configuration of the radar, the estimation of the RCS of the wind turbine is obtained.

Finally, assuming that the whole wind turbine is included within the beam cell resolution of the radar, the corresponding reflectivity value is calculated, as described in Table 4.

6 Conclusions

In order to estimate the potential impact of a wind farm on a weather radar service, one of the main issues to be analyzed is Wind Turbine Clutter reflectivity, which is directly related to the Radar Cross Section of wind turbines.

A preliminary study about possible interference problems is the most appropriate way to proceed in order to make the coexistence of wind energy and meteorological services possible. To do so, an estimation of the RCS of the wind turbines to be installed is a must. Although it is possible to obtain RCS values by conventional methods such as MoM and FDTD, they require detailed representations of the wind turbines' design and complex calculations, which are too time-consuming and difficult to obtain. On the contrary, typical values that do not take into account the particular features of the case under analysis may lead to significant errors in the impact analysis.

In this paper, the RCS patterns of wind turbines for the weather radar working frequencies have been analyzed. From the obtained results, it can be concluded that the mast is the main scatterer of the wind turbine, featuring a very directive lobe in the direction perpendicular to the slanted surface of the mast. The blades, by contrast, contribute to the total RCS of the wind turbine with secondary lobes that depend on the rotor orientation with respect to the illumination direction and the blades' position.

Based on the above-mentioned conclusions, a simple RCS model to characterize backscattering from wind turbines in the weather radar bands has been proposed. This model takes the RCS from the mast as a reference to estimate the main lobe of the RCS pattern of the whole wind turbine, and then calculates the maximum RCS from the blades taking into account the actual dimensions of the wind turbine model. Finally, and assuming that the whole wind turbine is included within the beam cell resolution of the radar, the WTC reflectivity can be directly obtained.

~~This simple WTC reflectivity model aims at being implemented in software planning tools and is expected to make the preliminary impact studies of wind farms on weather radar services easier.~~

The proposed RCS model can be used to estimate the maximum clutter due to the presence of a wind turbine, estimating the scattered power from the mast. On the other hand, even if the

Doppler radar under study uses a clutter filter that suppresses stationary objects, the rotating blades of a wind turbine might still be detected. As proved in (Norin, 2015), weather information from radar cells affected by a wind turbine is not always lost. In fact, when precipitation gives rise to reflectivity values stronger than those due to wind turbines, radar data could still be used. Therefore, the reflectivity model proposed in this paper is of interest not only to assess a potential detrimental impact on the performance of a weather radar, but also to evaluate to which extent this degradation might exist, if reflectivity values from precipitation and wind turbine blades are compared.

This simple WTC reflectivity model aims at being implemented in software planning tools and is expected to make the preliminary impact studies of wind farms on weather radar services easier.

Acknowledgements

A special note of thanks to José Miguel Gutiérrez (AEMet, Spanish Weather Agency) and Lars Norin (SMHI, Swedish Weather Agency), who provided insight and expertise from the perspective of a weather operator.

This work has been partially supported by the Spanish Ministry of Economy and Competitiveness (Ministerio de Economía y Competitividad , project TEC2012-32370) and the University of the Basque Country (Euskal Herriko Unibertsitatea, program for the specialization of the postdoctoral researcher staff).

References

Angulo, I, de La Vega, D., Rodríguez, O., Grande, O., Guerra, D. and Angueira, P.: Analysis of the mast contribution to the scattering pattern of wind turbines in the UHF band, 5th European Conference on Antennas and Propagation (EuCAP), 2011.

Angulo, I., Montalban, J., Canizo, J., Wu, Y., de la Vega, D., Guerra, D., Angueira, P., Arrinda, A.: A Measurement-Based Multipath Channel Model for Signal Propagation in Presence of Wind Farms in the UHF Band. IEEE Transactions on Communications, Vol.61, no.11, pp.4788-4798, Nov. 2013.

Angulo, I., de la Vega, D., Cascón, I., Cañizo, J., Wu, Y., Guerra, D., Angueira, P.: Impact analysis of wind farms on telecommunication services. Renewable and Sustainable Energy Reviews, Volume 32, April 2014, Pages 84-99, ISSN 1364-0321.

Grande, O., Cañizo, J., Angulo, I., Jenn, D., Danoon, L. R., Guerra, D. and de la Vega, D.: Simplified Formulae for the Estimation of Offshore Wind Turbines Clutter on Marine Radars, The Scientific World Journal, vol. 2014, Article ID 982508, 2014.

IEEE Std 211-1997, IEEE Standard Definitions of Terms For Radio Wave Propagation, 1997.

ITU-R (International Telecommunication Union): Technical and Operational Aspects of Ground-Based Meteorological Radars. Recommendation ITU-R M.1849; International Telecommunication Union; Geneva, Switzerland, 2009.

ITU-R and WMO (International Telecommunication Union and World Meteorological Organization): Handbook, Use of Radio Spectrum for Meteorology: Weather, Water and Climate Monitoring and Prediction, 2008.

Jenn, D.C.: Radar and Laser Cross Section Engineering, 2 ed.; Education Series, American Institute of Aeronautics and Astronautics: USA, 2005.

Knott, E.F.: Radar Cross Section Measurements, SciTech Publishing, 2006

Lemmon, J.J, Carroll, J.E., Sanders, F.H. and Turner, D.: Assessment of the Effects of Wind Turbines on Air Traffic Control radars, NTIA Technical Report TR-08-454, July 2008.

Norin, L. and Haase, G.: Doppler Weather Radars and Wind Turbines, Doppler Radar Observations - Weather Radar, Wind Profiler, Ionospheric Radar, and Other Advanced Applications, Dr. Joan Bech (Ed.), ISBN: 978-953-51-0496-4, InTech, 2012, DOI: 10.5772/39029. Available from: http://www.intechopen.com/books/doppler-radar-observations-weather-radar-wind-profiler-ionospheric-radar-and-other-advanced-applications/doppler-weather-radars-and-wind-turbines.

Norin, L.: A quantitative analysis of the impact of wind turbines on operational Doppler weather radar data, Atmos. Meas. Tech., 8, 593-609, doi:10.5194/amt-8-593-2015, 2015.

Rinehart, R.E.: “RADAR for Meteorologists”, 3rd ed. Rinehart Pub, 1997.

Siegel, K. M., Alperin, H. A., Bonkowski, R. R., Crispin, J. W., Maffett, A. L., Schensted, C. E. and Schensted, I. V.: Bistatic radar cross sections of surfaces of revolution. J. Applied Physics, vol. 26, no. 3, p. 297, Mar. 1955.

Skolnik, M.: Radar Handbook, 3rd ed. New York, New York: Mc-Graw-Hill, 2008

Tristant, P.: Impact of Wind Turbines on Weather Radars Band, World Meteorological Organization, CBS/SG-RFC 2006/Doc. 3.1, March 2006

Van Lil, E., Trappeniers, D., De Bleser, J., Van de Capelle, A: Computations of radar returns of wind turbines. In Proceedings of the 3rd European Conference on Antennas and Propagation, (EUCAP), Berlin, Germany, 23-27 March 2009; pp.3852-3856,.

Van Lil, E., Trappeniers, D., De Bleser, J., Van de Capelle, A: Computation of false echo zones and shadowing for aeronautical and weather radars. In Proceedings of the 4th European Conference on Antennas and Propagation (EUCAP), Barcelona, Spain, 12 April 2010; pp. 1–5.

Vogt, R. J., T. D. Crum, W. Greenwood, E.J. Ciardi, R.G. Guenther: Recent Efforts to Improve Estimates of and Mitigation of Wind Turbine Clutter Impacts on the WSR-88D. Preprints, 27th Int. Conf. on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, Seattle, WA, Amer. Meteor. Soc., Paper 3A.1, 2011.

WMO (World Meteorological Organization): Impact of Wind Turbines on Weather Radars Band, CBS/SG-RFC 2006/Doc. 3.1(6), 2005.

WMO (World Meteorological Organization): Commission for Instruments and Methods of Observation - Fifteenth session, WMO-No. 1064, Helsinki, 2–8 September 2010.

WMO radar database (available at http://wrd.mgm.gov.tr/, last accessed 15/Dec/2014)

Table 1. Wind turbine models selected for the simulations.

	Model 1	Model 2	Model 3
Mast height	78 m	100 m	119 m
Mast upper radius	1.15 m	1.80 m	2.40 m
Mast lower radius	1.75 m	2.70 m	3.60 m
Rotor diameter	87 m	90 m	112 m
Blade length	42.50 m	44.00 m	54.65 m
Rated power	2.0 MW	2.0 MW	3.3 MW

Table 2. Maximum RCS values from the mast and blades for the wind turbine models selected for the simulations.

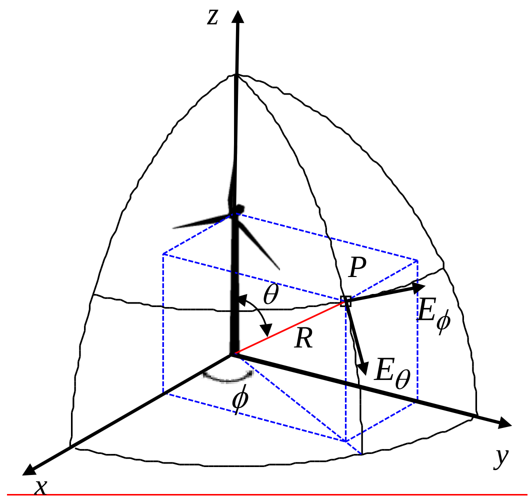
	WT Model 1			WT Model 2			WT Model 3		
	Mast (dBsm)	Blade (dBsm)	Difference (dB)	Mast (dBsm)	Blade (dBsm)	Difference (dB)	Mast (dBsm)	Blade (dBsm)	Difference (dB)
2.80 GHz	55.97	45.92	10.05	61.38	46.81	14.57	64.00	48.81	15.19
5.65 GHz	59.95	49.42	10.53	64.32	49.74	14.58	67.03	52.10	14.93
9.4 GHz	62.42	51.61	10.81	66.45	52.00	14.45	69.14	54.22	14.92

Table 3. Relation Δ between the relative scattering area of the mast and blades for the wind turbine models selected for the simulations.

WT Model 1	WT Model 2	WT Model 3
9.90 dB	12.65 dB	13.38 dB

Table 4. Simplified model for estimating WTC reflectivity in weather radar bands.

Model for calculating wind turbine clutter reflectivity
1- Wind turbine RCS
$\sigma_{mast} = 10\log_{10}\left(\frac{2\pi}{\lambda} rL^2 \sin(\theta+\alpha)\left(\frac{\sin\left(\frac{2\pi}{\lambda}L\cos(\theta+\alpha)\right)}{\frac{2\pi}{\lambda}L\cos(\theta+\alpha)}\right)^2\right)$ (dBsm) for $\theta\|_{\sigma_{mast}\geq\sigma_{blades}}$ $\sigma_{blades} = 10\log_{10}\left(\frac{2\pi}{\lambda} rL^2\right) - 10\log_{10}\left(\frac{4H(r_1+r_2)}{w\cdot l}\right)$ (dBsm) for $\theta\|_{\sigma_{mast}<\sigma_{blades}}$ Where: $\alpha = \tan^{-1}\left(\frac{r_2-r_1}{H}\right)$ and $L = \frac{H}{\cos\alpha}$
2- Wind turbine clutter reflectivity
$z = \frac{16\ln(2)}{\pi^6 c}\cdot\frac{\lambda^4}{\theta_0\Phi_0\tau}\cdot\frac{\sigma}{\|K\|^2R^2}$, where σ is the RCS in linear values (m^2)



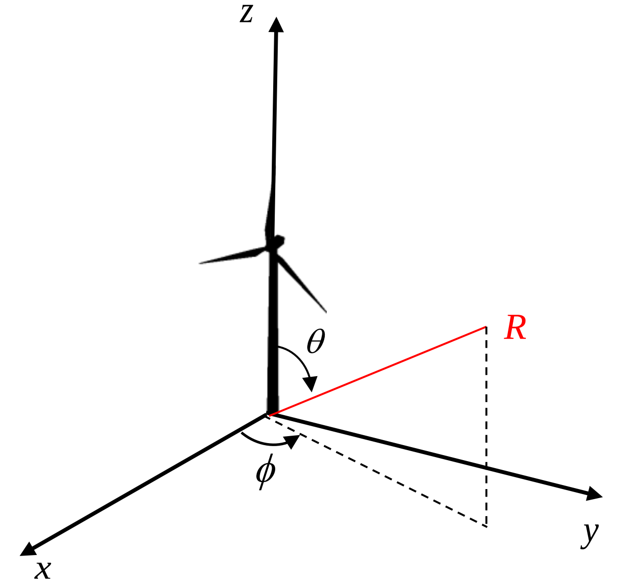


Figure 1. Spherical coordinate system used in the RCS calculations~~–~~. *R* represents radar location~~(Grande, 2015)~~.

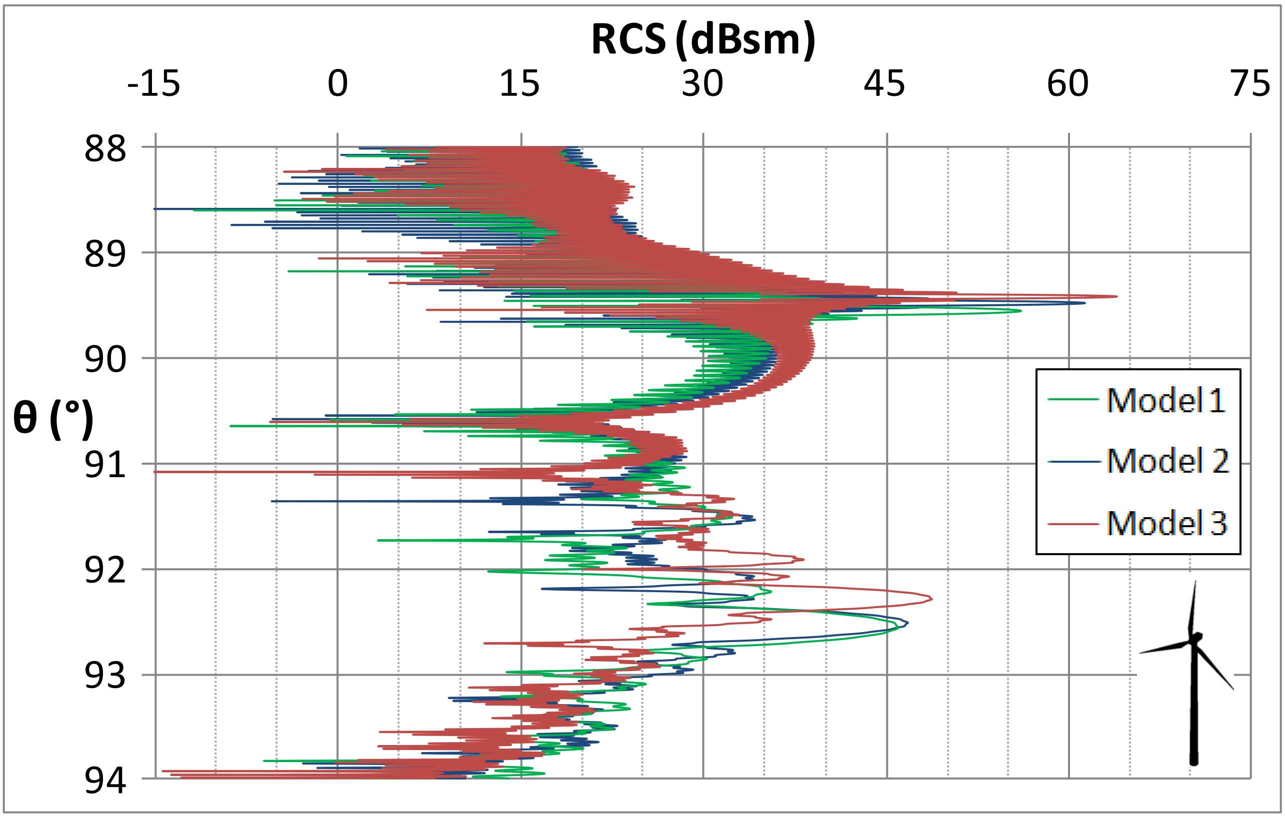


Figure 2. Vertical sections of RCS patterns (Φ = 5º) for wind turbine models 1 to 3 at frequency 2.80 GHz. Rotor position is indicated in the lowest right corner.

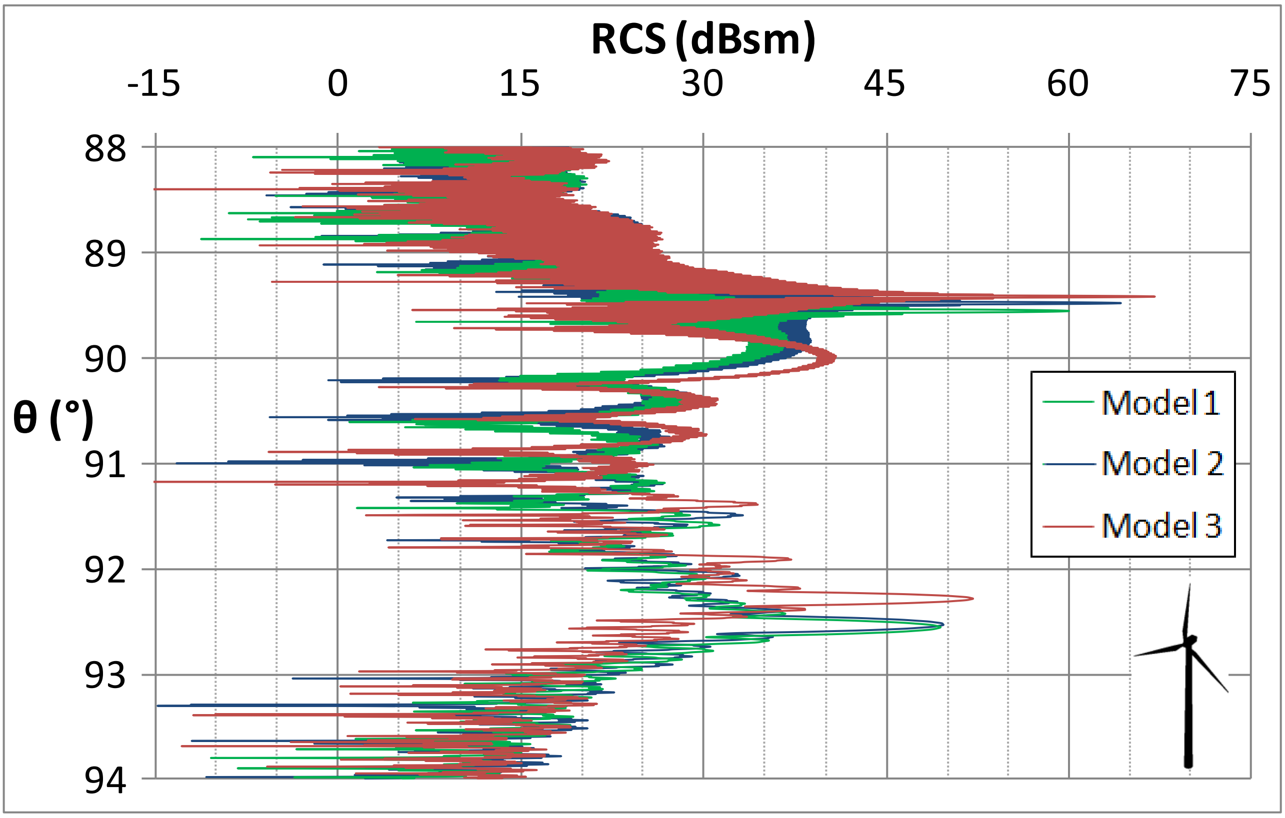


Figure 3. Vertical sections of RCS patterns ($\Phi = 5º$) for wind turbine models 1 to 3 at frequency 5.65 GHz. Rotor position is indicated in the lowest right corner.

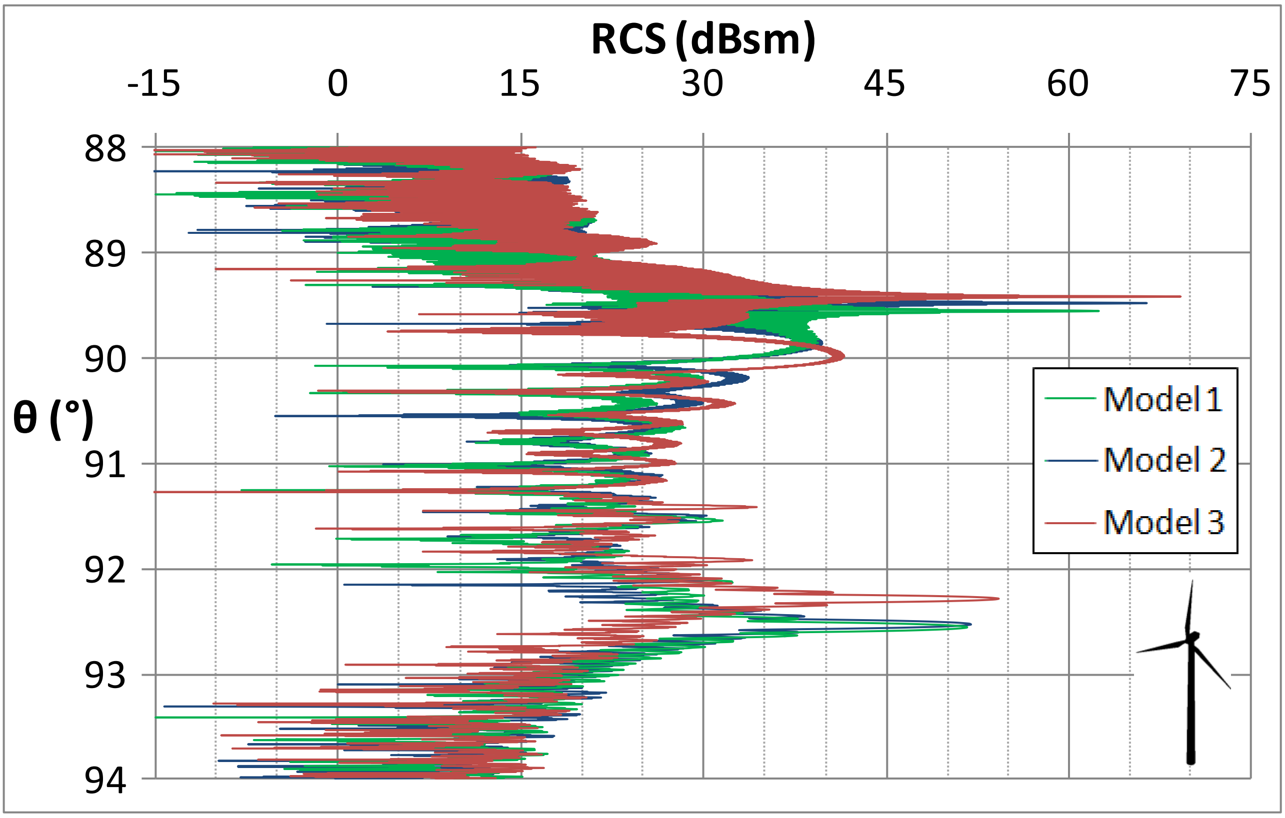


Figure 4. Vertical sections of RCS patterns ($\Phi = 5º$) for wind turbine models 1 to 3 at frequency 9.40 GHz. Rotor position is indicated in the lowest right corner.

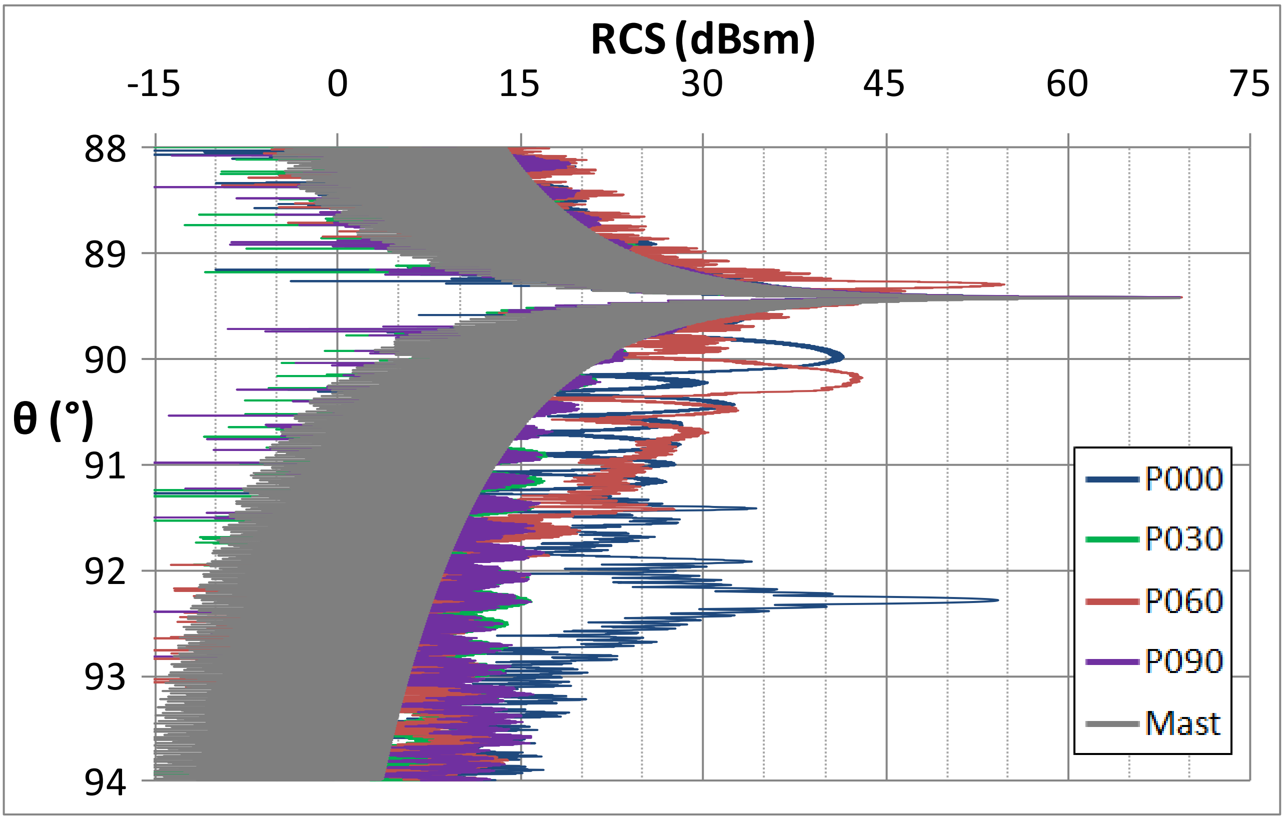


Figure 5. Vertical sections of RCS patterns (Φ = 5º) for wind turbine model 3 at frequency 9.40 GHz. Legend entries starting with PXXX indicate the position of the upper blade (being P000 vertical right position and P090 horizontal position).

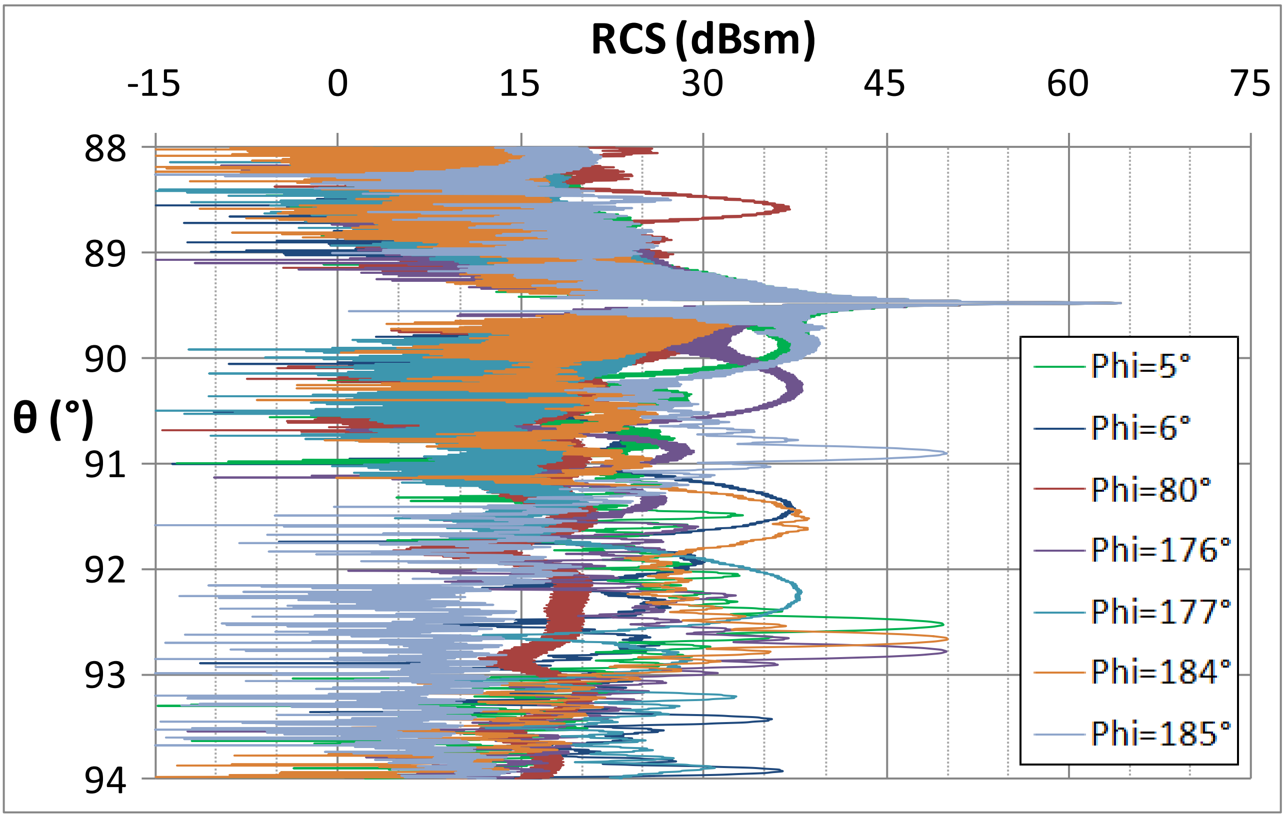


Figure 6. Vertical sections of RCS patterns (Φ = 5º, 6º, 80º, 176º, 177º, 184º, 185º) for wind turbine model 2 at frequency 5.65 GHz and rotor position P000.

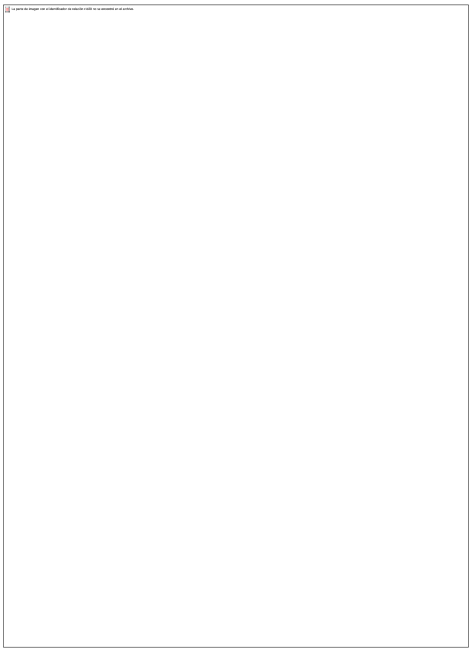


Figure 7. Geometry for the RCS calculation of the mast

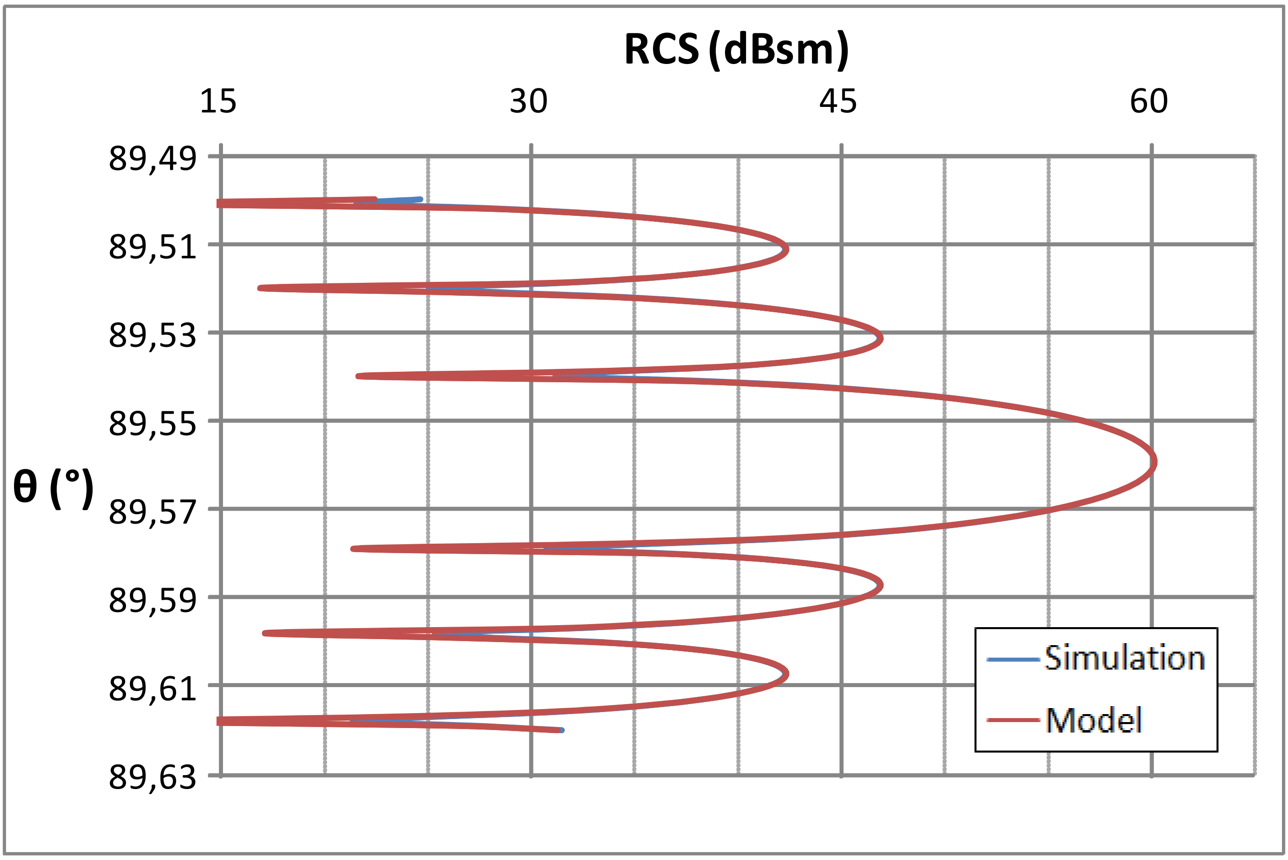


Figure 8. RCS pattern obtained by simulation vs RCS values obtained by the proposed simplified model for the mast of wind turbine model 1 and frequency 5.65 GHz.

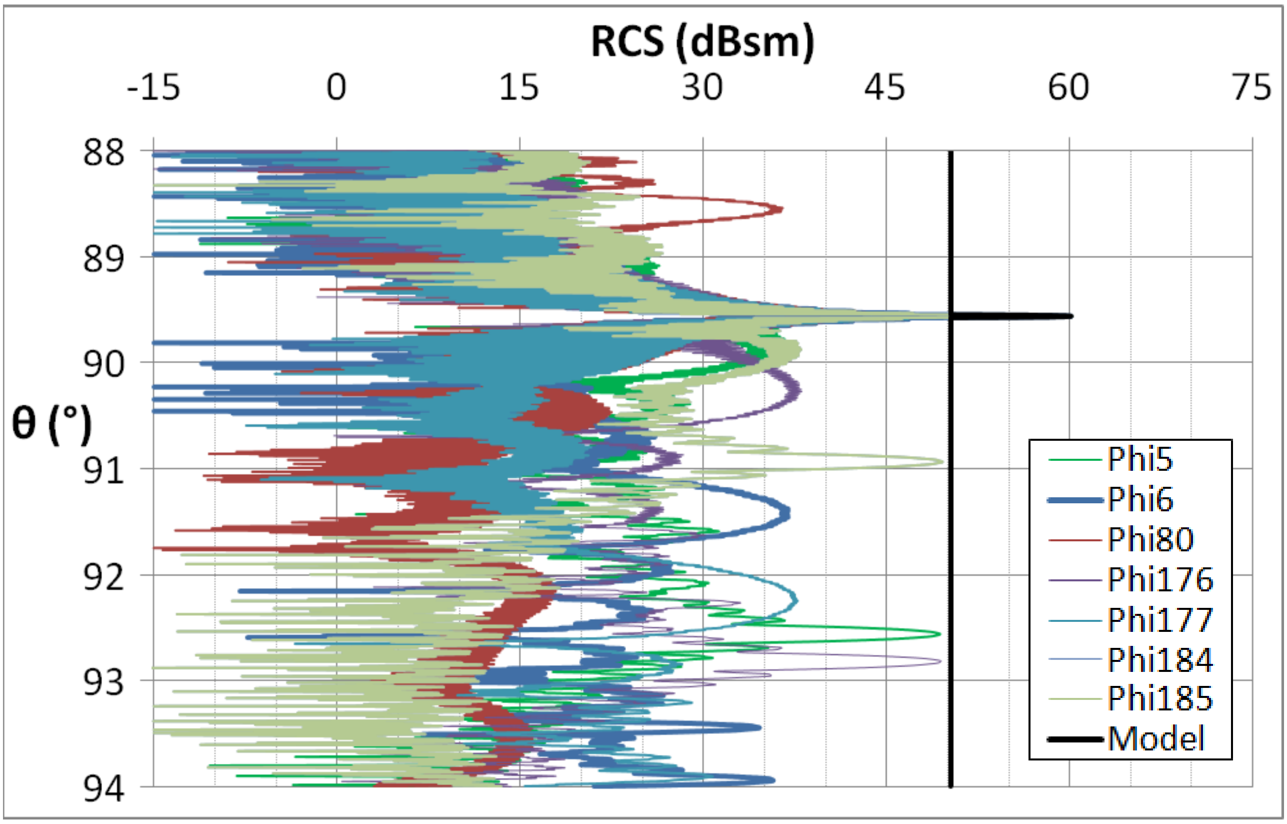


Figure 9. Vertical sections of RCS patterns (Φ = 5º, 6º, 80º, 176º, 177º, 184º, 185º) for wind turbine model 1 (Frequency 5.65 GHz, Rotor position P000) and result of the proposed model (black line).