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# ***Interactive comment on “Estimating reflectivity values from wind turbines for analyzing the potential impact on weather radar services” by I. Angulo et al.***

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## General Comments

The content of this manuscript aims at evaluating the impact from windmills on weather radars. More in depth, the work focuses on estimating the wind turbine clutter (WTC) reflectivity by means of a new proposed model, which in turn should allow quantifying this kind of affectation. The proposed new model consists on a set of simplified reflectivity formulae. This set is valid for a wide frequency range and different wind turbines. The most part of this work focuses on providing an accurate Radar Cross

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Section (RCS) of wind turbine through characterizing numerical results from a Physical Optic (PO) simulation technique. This work shows an effort into reproducing a real scenario, and hence, the new contribution seems to be useful for Weather Radar Services in the task of quantifying this kind of affectation. However, in an actual scenario, other elements like the terrain or secondary lobes can take an important role in a real WTC reflectivity map. In this regard, a little effort on a final validation to corroborate the WTC reflectivity model (model accuracy) would highly consolidate this work. Somehow, in the manuscript should appear some discussion that includes the disadvantages or limitations of the proposed model regarding the elements that have not been considered in the analysis. On the other hand, with the aim to corroborate the proposed new work, the following general remarks (A-D) should be considered for the whole manuscript: A) Consider depicting or representing more clear for the reader the coordinates used into the overall text, specially with the different angular coordinates (e.g. 'alfa' and 'tetha' in expression '(3)', and 'tetha' in figures 1 and 7). B) Consider reorganizing Section 4 and 5, as some contents about results from simulations need to be linked better to Subsection 4.2. When doing this, consider creating a new subsection for the analysis, rewording its conclusions (paragraphs 3 and 4 in page 1486), in order to emphasize that these are the base for characterizing the backscattering in Section 6. C) The expressions which are the base of the proposed formulae should have a better detailed deduction (e.g. expressions '(2)' and '(3)' in Section 6). D) The references should be checked regarding each citation in the overall text. In this regard, peer-reviewed references should take a significant role. These general remarks would be also included in the specific comments below.

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. Please note that the changes have been applied to the version of the paper that was uploaded after the changes suggested by Anonymous Referee #1.

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## Specific Comments

Abstract 1. Page 1478, Second Paragraph Consider mentioning how the scenario for the developed model is just to situate the reader. As suggested by the reviewer, an additional comment on the scenario has been included in the abstract: “For the proposed model, a representative scenario has been chosen, where both the weather radar and the wind farm are placed on clear areas, i.e., wind turbines are supposed to be illuminated only by the lowest elevation angles of the radar beam.”

Section 1 1. Whole section Review the references citation. Regarding the references section 'Norin, 2012' should be 'Norin and Haase, 2012', 'Gallardo, 2011' does not appear and the same for 'Grande, 2015', 'ITU-R, 2009', etc. The references section and the references citations have been reviewed through the text. In particular, citations to (Norin, 2012) have been changed to (Norin and Haase, 2012). The references that correspond to (Isom et al., 2008), (Gallardo et al., 2011) and (Grande et al., 2015) have been included in the References section: “Gallardo-Hernando B., Muñoz-Ferreras J.M., Pérez-Martínez F., Aguado-Encabo F.: Wind Turbine Clutter Observations and Theoretical Validation for Meteorological Radar Applications, Radar, Sonar & Navigation, IET, vol.5, no.2, pp.111-117, Feb. 2011.” “Grande, O., Angulo, I., Jenn, D., Aguado, F., Guerra, D., and de la Vega, D.: Analysis of Wind Turbines Radar Cross Section for Analyzing the Potential Impact on Weather Radars, 2015 9th European Conference on Antennas and Propagation (EUCAP), 12-17 April 2015.” “Isom, B. M., Palmer, R. D., Secrest, G. S., Rhoton, R. D., Saxion, D., Allmon, T. L. , Reed, J., Crum, T., Vogt, R., Detailed Observations of Wind Turbine Clutter with Scanning Weather Radars, Journal of Atmospheric and Oceanic Technology, vol. 26, pp. 894-910, 2008.” The reference that corresponds to (ITU-R, 2009) was already included in the paper: 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. 2. Page 1479, Line 2 Add a reference to reinforce the factors proposed as the main factors. Refer-

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ences to (Gallardo-Hernando, 2011), (Norin and Haase, 2012) and (Norin, 2015) have been included to reinforce the main factors mentioned in the text. 3. Page 1480, Line 1 Avoid the use of the word 'interferences' in this context. Consider 'afectations', 'impacts' or a similar word in this case. As suggested by the referee, "interferences" has been replaced by "impacts" in this case.

Section 2 1. Page 1480 Avoid the use of pharenthesis to enclose statements and use commas instead. Reword this paragraph. The first paragraph of Section 2 was already changed according to the comments of Referee #1: "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)" 2. Page 1480, First Paragraph 'Norin and Haase, 2012' can be included to reinforce the statement about the error classification. The suggested citation has been included in the text. 3. Page 1480, Fourth Paragraph Consider adding some other reference about the impact due to signal blockage. See, for example, a suggested reference below this text. Mention that this non-desired phenomena is not treated in this manuscript. The suggested reference has been included in the text and cited in Section 2. "Belmonte, A.; Fabregas, X., Analysis of Wind Turbines Blockage on Doppler Weather Radar Beams, IEEE Antennas and Wireless Propagation Letters, vol.9, pp.670-673, 2010" In regard to the second suggestion, according to a comment from Referee #1, a sentence was added at the end of the third paragraph 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." 1. Page 1480, Fifth Paragraph Avoid the use of parenthesis to enclose statements and use commas instead. Consider including some reference to reinforce the statement at the end. The text has been reworded to avoid the use of parenthesis and some references have been included to reinforce the statement. "As the RCS of a

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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 (Angulo et al., 2011), (Grande et al., 2014)”.

#### Section 4

Section 4.1 1. Page 1481 In a real scenario, the backscattering from windmills can contain important differences depending on the terrain surface: In a flat area or over a hill, the reflectivity will be different from irregular surfaces or with important mountains behind. Reword this section to indicate that, in a more realistic calculation, the texture of the terrain should be included. Please note that comments by Referee #1 led to a change in the organization of the paper. The considerations of the analysis are now included in Section 3.2. According to the reviewer’s comment, a last point has been included in Section 3.2 – Considerations of the analysis, as detailed in the response to the next comment. 2. Page 1482 Add some words to justify that both the effect of secondary lobes and the terrain are excluded from the analysis. The RCS concept is defined to be independent of both the propagation effects, including potential terrain interactions, and the radar characteristics, including radiation pattern. However, the calculation of the reflectivity values may include additional parameters to account for these effects. For example, at long distances, the beam curvature and losses due to propagation in the troposphere might be included in the radar equation; terrain reflections may be considered in the characterization of the radiation pattern of the radar; the gain value in Eq. (11), (12) and (13) might refer to the gain of secondary lobes, etc. In order to simplify the analysis of the reflectivity values presented in the paper, without loss of generality, the calculation of the reflectivity values shown in Section 5 does not include these additional effects. Therefore, as indicated in the response to the previous comment, a remark about the potential effects of terrain and the secondary lobes has been included in Section 3.2 – Considerations of the analysis. “- Reflectivity

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model. The calculation of the reflectivity value from a wind turbine is based on considering Line of Sight (LoS) propagation. In real scenarios, interactions from the ground and terrain should be taken into account, e.g., potential shadowing effects (Norin and Haase, 2012). Moreover, it is assumed that the wind turbine is being illuminated by the main lobe of the radiation pattern of the radar.”

Section 4.2 Section 4.2.1 1. Whole section Generally, simulation tools take into account some assumptions, as for example standard conditions for modelling the radar beam propagation in the troposphere. In this work, apart from the reference given (Jenn, 2005) about the simulation software used, add some extra information for the reader explaining its principal assumptions. Please note that the descriptions of the PO method and the software tool are now included in Section 3.1.1 - Simulation tool and wind turbine models. The first paragraph of Section 3.1.1 has been modified to add extra information about the PO theory assumptions. Further details on the theory behind the software tool can be found in the references and are not included in the paper in order to avoid redundant information. With respect to modeling the radar beam propagation in the troposphere, as the simulation tool provides RCS values, propagation effects are not included. The first paragraph of Section 3.1.1 is now as follows: “The present study is based on the accurate assessment of RCS values of wind turbines by applying the Physical Optics (PO) theory. The PO theory is a high-frequency approximation method that provides accurate results for electrically large objects ( $L \geq 10\lambda$ ) and for observation points near the specular direction. 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. The software tool does not include the effect of multiple reflections, diffraction or surface waves. More in depth descriptions of the Physical Optics Method and the simulation tool can be found in (Jenn, 2005), (Grande et al., 2014), (Grande et al., 2015).” Section 4.2.2 1. Page 1484, Line 19 Replace ‘currently’ with ‘usually’ or give some reference instead. Please note that wind turbine models are now

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described in Section 3.1.1. “Currently” has been replaced by “usually” in the mentioned sentence. Section 4.2.3 1. Page 1484 Replace ‘accuracy’ with ‘precision’. “Accuracy” has been replaced by “precision” in the title of the new Section 3.1.2. – Simulation precision. 2. Page 1484, Line 22 Replace ‘previously’ for the corresponded section. Add more information in this subsection about the requeriments of the simulation procedure. Due to the changes in the organization of the paper proposed by Referee #1, the “previously” mentioned here was already removed from the text. The first paragraph of Section 3.1.2 has been reworded to add more information about simulation conditions, as follows: “The analysis is based on the assessment of backscattering patterns for a set of elevation angles (variation in  $\theta$ ), as detailed in Section 3.2; and different conditions of rotor orientation with respect to the radar (variation in  $\Delta d$  from  $0^\circ$  to  $185^\circ$ ) and blades position (rotating blades).” 3. Page 1485, Second Paragraph Add a link at the end to indicate where in this manuscript the reader can find the separated analysis (mast, nacelle and single blades). The following sentence has been added at the end of the paragraph: “(…) as described in Section 4 and shown in Fig. 2 to Fig. 7.”

Section 5 1. Page 1485 Consider combining this section with the previous one, as it seems that the analysis from simulation outputs is an important part of the methodology to characterise the scattering for the proposed model. Moreover, reword this section with the aim to reinforce all the conclusions of the analysis. Former Section 5, now Section 4 - Simulation results and analysis is, as commented by the reviewer, the basis for the proposed scattering model. Therefore, the authors consider that it is important to maintain the analysis of the simulation results as an independent section. In our opinion, this improves the readability and understandability of the paper, and helps the reader identify the results of the simulations as an important part of the contribution presented here. On the other hand, according to the referee’s comment, the conclusions of the analysis have been reworded as follows: “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

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lobe normal to the slant surface, extremely directive in the vertical plane and omnidirectional in the horizontal plane. The scattering from the mast can be approximated by the RCS of a right circular cylinder, which will be the basis of the proposed model for calculating the wind turbine RCS values, as later described in Section 5.1. The blades, by contrast, provide variable levels of signal scattering depending on the rotor orientation and blade positions. Despite the variability of the scattering from the blades, their contribution to the total RCS of the wind turbine is always significantly lower than the amplitude of the main lobe due to the mast. Therefore, in order to provide a worst-case assumption with respect to the signal scattered by the blades, the proposed scattering model will provide an upper limit to the RCS values from the blades, as will be shown in Section 5.2.”

2. Page 1485, Line 10 Replace 'As previously mentioned' with a phrase to clarify in what section is mentioned. "As previously mentioned" has been replaced by "As mentioned in Section 3.2".

3. Page 1485, Fifth Paragraph Reword this paragraph to indicate better the coordinate system that is being used. Also in line with the comments from Referee #1, and 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,  $\theta$  is the angle from the zenith that defines the radar position in the vertical plane, and  $\phi$  specifies the horizontal position of the radar with respect to the rotor orientation, i.e., with respect to the rotor shaft axis" These changes aim at providing an easier interpretation of the results in Section 5.

4. Page 1486, Line 7 Replace 'Obviously' with a more proper expression, as for example 'As it can be expected'. The mentioned expression has been replaced in the text according to the reviewer's comment.

Section 6 Section 6.1 1. Whole section Consider reorganizing this subsection to de-

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scribe better the angular coordinates, as in figure 7 seems that does not appear the half cone angle, 'alpha'. Consider describing a little bit more in depth how is deduced the expression (2) from the formulae in Siegel (1995), as it is the base for the proposed model. If you prefer, include an appendix with the procedure. Figure 7 has been changed to include the representation of the half cone angle  $\alpha$ . Regarding the deduction of the expression (2), the main simplifications from the formulae in (Siegel et al., 1995) are described in a previous reference from the authors (Angulo et al., 2013). Therefore, this reference has been cited and the text and the minor simplifications applied for the monostatic case described as follows: "The expression proposed in (Siegel et al., 1995) was adapted to a circular cylinder and simplified to avoid indeterminate forms as described in Appendix A of (Angulo et al., 2013). As for radar applications only backscattering is of interest, the formulae in (Angulo et al., 2013) for a circular cylinder can be further simplified assuming that  $\theta_t = \theta_r$  and  $\phi_d = 0^\circ$  and expressed as:"

2. Page 1488, Line 19 Avoid the use of parenthesis. The text has been changed as follows: "For all the analyzed cases, i.e., for the three wind turbine models and three working frequencies under consideration, the mean (...)"

Section 6.2 1. Page 1489, First Paragraph Remove 'as demonstrated in the simulations' or replace it with a more concrete reference to the section number where it is demonstrated. The statement "as demonstrated in the simulations" has been replaced by "as shown in Fig. 5 and Fig. 6".

2. Page 1489, Second Paragraph Reword this paragraph reorganizing the order of the statements. According to the referee's comment, the paragraph has been reworded as follows: "Therefore, instead of obtaining a complete scattering model for the blades, a simpler approach to this issue is characterizing the maximum value of the scattering from the blades. To do so, the maximum RCS value due to the blades for each wind turbine model will be obtained. 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."

3. Page 1489, Line 19 Replace 'Obviously' with the section where it is demonstrated the frequency dependence of maximum RCS. "Obviously" has been replaced by "As shown in Section 4 when comparing Fig. 2, Fig. 3 and Fig. 4,"

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Page 1489, Line 25 Justify a little bit more why the RCS must be proportional to their corresponding dimensions. The text has been completed as follows: “(. . .), the relation between the maximum RCS from the mast and the maximum RCS from the blades must be proportional to their corresponding dimensions, as the RCS of an object generally depends upon its physical size when its orientation relative to the LoS to the radar is such that a significant area of the object is illuminated (Knott, 2006), (Skolnik, 2008).” 5. Page 1490, Line 1 Justify better the reason why to consider only the 50 % of impact regarding the blade design. There would be important differences in results considering other percentages? The assumption of 50% is related to the reference (Spera and Sengupta, 1994) Spera, D.A., Sengupta, D.L., Equations for Estimating the Strength of TV Signals Scattered by Wind Turbines, NASA Contractor Report 194468, May 1994. According to the referee’s comment, the text has been changed as follows: “As a very simple approach, the blade can be represented by a triangle. However, in real blade designs, the profile of the blade rotates from hub toward to the blade tip in order to maintain the angle of attack (Gipe, 2004). Considering this twist angle of the blades, the area of this triangle will be never completely facing the radar. In (Spera and Sengupta, 1994) it is empirically obtained that the signal scattering efficiency of a blade  $\eta$  is dependent on the blade twist according to:  $\eta = \exp(-2.30\Delta\beta)$ , where  $\Delta\beta$  is the total blade twist from root to tip (rad). This total twist depends on the blade length and design. In commercial wind turbines, total blade twist is typically about 20 degrees. For example, a Vestas V27 model has a total blade twist of 13 degrees (Gipe, 2004), which provides scattering efficiency values around 0.45-0.60. As a rough approach, we will consider a scattering efficiency of 50% for the wind turbine blade. As later shown in Table 2 and Table 3, this assumption leads to a good approximation of the signal scattered by the blades.” Additional reference included: Gipe, P., Wind Power: Renewable Energy for Home, Farm, and Business, 2nd edition, Chelsea Green Publishing, April 1, 2004. 6. Page 1490, Fourth Paragraph Consider including a new table with the values of the differences between results from Table 2 and 3, and the results obtained from expression (9). A comparison of the maximum RCS of the blades from PO simulations

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and the maximum RCS values calculated according to Eq. (10) (former Eq. (9)) is now shown in Table 4. Section 6.4 1. Page 1492, Line 4 Replace 'This' with 'The proposed'. The suggested change has been included in the text. 2. Page 1492, Final paragraph Consider rewording the first or the second 'is obtained' so that the text would be more readable. The first "is obtained" has been replaced by "is completed".

Section 7 1. Page 1494, Fourth Paragraph Secondary lobes have not been considered in the analysis of this manuscript. Consider rewording this paragraph in order to be more consistent with the previous analysis. For the sake of clarity, the following sentence has been changed to remove the term "main lobe" from the indicated paragraph: "This model takes the RCS from the mast as a reference to estimate the maximum value of the RCS pattern of the whole wind turbine, (. . .)" However, it should be noted that the term "main lobe" in the previous sentence referred to the main lobe of the scattering pattern of the wind turbine, and not to the main lobe of the radar beam.

References 1. Whole section Check all references in the manuscript, specially the ones that only appear in the previous text citation. Suggested references: Belmonte A., Fàbregas X., 2010: Analysis of Wind Turbines Blockage on Doppler Weather Radar Beams, IEEE Antennas and Wireless Propagation Letters, Vol. 9. The references section and the references citations have been reviewed through the text. The suggested reference has been included and cited in the text.

Please also note the supplement to this comment:

<http://www.atmos-meas-tech-discuss.net/8/C853/2015/amtd-8-C853-2015-supplement.pdf>

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