Abstract—The existing models to characterize signal scattering from wind turbines in the UHF band are based on the characteristics of the blades and do not consider the potential contribution from the mast. This paper aims to estimate the Radar Cross Section of a wind turbine and its components in order to determine the relative significance of the mast for the development of future scattering models.

I. INTRODUCTION

A horizontal axis wind turbine is normally composed of a metallic supporting tower, a metallic nacelle where the fundamental machinery is located and a rotor with three blades made of non-metallic materials.

Due to their large size and the continuous movement of their parts, wind turbines may cause different effects on the radioelectric signals. Therefore, if wind farms are located near telecommunication infrastructures, there might be quality degradation of the provided services. One of the potentially affected services is television broadcasting.

Several studies for the characterization of the signal scattering from wind turbines were carried out in the 70’s and 80’s. These studies are essentially theoretical, and they aim to provide simple models for estimating the scattering pattern of wind turbines and determine their potential impact on television reception quality [1]-[5]. These scattering models are based on the dimensions and/or materials of the blades, not considering the potential reflected signals from the nacelle or mast. The reason why these models are based on the blades may lie in the evolution of the wind turbines; since most of the above-mentioned studies were carried out, the blades of the wind turbines have evolved from metallic to composite materials, whilst the grid masts have been replaced by tubular metallic masts.

The ITU-R has recently asked for studies that propose new models and methods of calculation to determine the signals reflected by the wind turbines and their effect on digital television reception quality [6]. In response, recent empirical studies have been carried out. The obtained results suggest that the mast generates significantly high values of scattered signals [7]. Moreover, the backscattering signals from the wind turbines may be detected in a receiver as a varying multipath channel that might increase the minimum requirements for a satisfactory reception of the digital television service [8]-[9]. These aspects should be revised and the outcomes considered for the development of future scattering models.

II. OBJECTIVES

The present study is based on the estimation of the Radar Cross Section [10] of a wind turbine by using the Physical Optics method. Simulations aim to determine the relative significance of the mast on the RCS of the whole wind turbine, in order to evaluate the validity of the theoretical models for the UHF band, which only consider the contributions from the blades.

For this purpose, a characterization of each element of the wind turbine has been carried out for different incident and scattering directions. Furthermore, different illumination conditions are also analyzed.

III. METHODOLOGY

The Physical Optics (PO) method [11]-[12] is based on the estimation of the field strength values radiated by the induced currents on the illuminated portions of a target surface. The current values over the illuminated portions are estimated as the current at each point that would be found on a tangent plane of similar material, and set to zero over the shadowed portions. The scattered far field strength is then obtained by integrating the approximate currents. The Physical Optics is a high-frequency approximation method that provides accurate results for electrically large objects (L≥10λ) and for observation points near the specular direction. When the observation point is far from the specular direction or the body is electrically small, the behaviour of the current at the edge of the illuminated surface significantly affects the scattered field [11].

For electrically large targets, one of the most common approaches to estimate the RCS is to decompose its surface into basic geometric shapes and obtain the total target RCS as a sum of the contributions from each of these elements [11]. For instance, any large, smooth surface can be approximated by a collection of small triangles placed edge-to-edge over the surface [13].

POFacets is an implementation of the Physical Optics approximation for bistatic or monostatic RCS estimation of complex targets developed in Matlab [14]. For the study presented in this paper, CAD models of wind turbines composed of multiple triangles have been designed. The size of the triangles is small enough to accurately define the wind turbine surfaces but still fulfilling the condition of being electrically large for the frequencies assigned to digital
television broadcasting within the UHF band. The software tool does not include the effect of multiple reflections, diffraction or surface waves.

**IV. WIND TURBINE MODEL**

The wind turbine representation used for the simulations is based on an actual model developed by one of the main wind turbine manufacturers [7]. The main characteristics of the wind turbine are listed in Table I. It should be noted that the mast is not a cylinder but a truncated cone.

<table>
<thead>
<tr>
<th>TABLE I WIND TURBINE CHARACTERISTICS</th>
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<tr>
<td>Mast height</td>
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<td>Diameter of the bottom of the mast</td>
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<td>Diameter of the top of the mast</td>
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<td>Rotor diameter</td>
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For the simulations, perfect electric conductor materials are assumed for the whole wind turbine surface. This is not the real case, because as previously commented, blades are normally made of composite materials as fibreglass. However, this assumption overestimates the blades contribution and thus provides a worst-case estimation of the mast contribution to the RCS of the whole wind turbine.

**V. RESULTS**

RCS simulations for the different components of the wind turbine have been carried out separately in order to characterize their horizontal and vertical patterns. Incident angles are indicated by subscript “i” and scattering angles by subscript “s”. Details about the coordinate system used can be found in the Appendix.

**A. Scattering Pattern of the Mast**

First, the vertical scattering pattern of the mast is analyzed when it is illuminated perpendicularly to its axis ($\theta_i = 90^\circ$, $\phi_i = 0^\circ$). Fig. 1 shows the RCS of the mast in the vertical plane containing the incident signal as a function of the elevation angle ($0^\circ \leq \theta_s \leq 180^\circ$). A significant variation of the scattering pattern with the elevation angle is observed in a narrow sector around the horizontal plane, i.e., the highest RCS values gather in a narrow lobe in the direction perpendicular to the mast. More precisely, the maximum is for $\theta_s \approx 89^\circ$ due to the fact that the mast is a truncated cone, and as such, the specular direction is slightly displaced above the horizontal plane.

A significant variation of the scattering pattern with the elevation angle is observed in a narrow sector around the horizontal plane, i.e., the highest RCS values gather in a narrow lobe in the direction perpendicular to the mast. More precisely, the maximum is for $\theta_s \approx 89^\circ$ due to the fact that the mast is a truncated cone, and as such, the specular direction is slightly displaced above the horizontal plane.

Fig. 2 shows the horizontal RCS variation of the mast ($\phi_s = 90^\circ$) for the same illumination conditions ($\theta_i = 90^\circ$, $\phi_i = 0^\circ$). Little variation of the bistatic scattering for azimuth angles $-90^\circ \leq \phi_i \leq 90^\circ$ and a narrow forward lobe stronger than the backscattering can be observed in the figure. In fact, when the body dimensions are significantly larger than the incident wavelength, the forward lobe is proportional to the projected area of the target. The large forward scatter is normally subtracted from the incident field thereby creating a shadow behind the target [13], and it seems to have minor effect on the digital television reception quality [9].

**B. Scattering Pattern of the Nacelle and Blades**

Secondly, the scattering pattern of the nacelle and blades is analyzed in an analogous manner to the previous case.

Fig. 3 shows the vertical scattering pattern of the nacelle and blades when illuminated perpendicularly to its axis ($\theta_i = 90^\circ$, $\phi_i = 0^\circ$). The vertical variation is not as specular as in the case of the mast due to the complex structure of nacelle and blades.

RCS variation of the nacelle and blades in the horizontal plane when maintaining the incident direction is shown in Fig. 4.
Horizontal scattering pattern of the nacelle and blades shows more variability than the horizontal pattern from the mast, with a backscattering lobe and a stronger forward lobe.

C. Scattering Pattern of the Wind Turbine

Finally, the RCS values of the mast, the blades and nacelle and the whole wind turbine as a function of the elevation angle \( \theta_s \) are compared in Fig. 5. The wind turbine is illuminated horizontally, the rotation plane of the blades facing the incident signal \( \theta_i = 90^\circ, \phi_i = 0^\circ \).

A significant decreasing of the reflected signal from mast with respect to the signal reflected from blades for directions far from the horizontal plane is observed. Therefore, the amplitude of the signal scattered by the mast is the main contribution to the RCS of the whole wind turbine only for a limited sector of the vertical plane.

However, the highest RCS value of the vertical pattern of the wind turbine corresponds to \( \theta_i \approx 89^\circ \), coinciding with the maximum of the vertical scattering pattern of the mast.

In order to observe the mast contribution to the RCS of the whole wind turbine with respect to the azimuth angle \( \phi_s \), the RCS variation is obtained for this maximum of the vertical pattern, \( \theta_i = 89^\circ \). Hence, the results included in Fig. 6, instead of corresponding to the same horizontal plane, correspond to the circular conical surface formed for \( \theta_i = 89^\circ \) around the wind turbine.

Results show that the RCS of the mast is significantly greater than the generated by blades and nacelle in most of the bistatic directions.
D. Different Illumination Conditions

The radiation pattern is also analyzed when the wind turbine is not illuminated horizontally. Fig. 7 shows the vertical variation of the RCS values of the components and the whole wind turbine when it is illuminated 10° above the horizontal plane, and the blades of the turbine are facing the incident signal ($\theta_i = 80^\circ$, $\phi_i = 0^\circ$).

Results show that the maximum value of the scattering pattern of the mast is in the specular reflection direction ($\theta_s \approx 99^\circ$). Moreover, the maximum value of the RCS vertical variation of the wind turbine again coincides with the maximum of the RCS of the mast.

Therefore, the comparative of the variation of the RCS values of the mast, the nacelle and blades and the wind turbine as a function of the azimuth angle $\phi_s$ is obtained for the maximum of the vertical pattern, $\theta_s = 99^\circ$.

Results show that, in the circular conical surface formed for $\theta_s = 99^\circ$, the RCS of the mast is significantly greater than the generated by blades and nacelle in most of the bistatic directions.

VI. CONCLUSIONS

The most important scattering models for determining the impact of wind turbines on television services are based on the signals reflected by flat blades.

This study estimates the scattered signal generated by each component of the wind turbine in order to evaluate the relative contribution of the mast to the bistatic scattered signal by the whole wind turbine. RCS patterns have been obtained and analyzed for different observation locations and several illumination conditions.

The results show that the mast generates reflected signals of significant amplitude within a very directive lobe in the specular direction of the vertical plane. It can be observed that the mast contribution within this lobe is significantly higher than the contribution of the other components of the wind turbine, not only in the incident direction but also as the observation angle varies in azimuth ($\phi_s$). Consequently, the elevation angle of the incident signal is a key factor to determine the direction of the maximum of the scattering pattern.

Estimation models used for planning purposes are normally based on worst-case assumptions. The analyzed simulations demonstrate that the RCS of the whole wind turbine is underestimated if the mast contribution is not considered. As a result, the signal scattered by the mast should be included in the development of future scattering models for wind turbines in the UHF band.

APPENDIX

For the sake of clarity, the standard spherical coordinate system used to specify incident and observation (scattering) directions is shown in Fig. 9. Incident angles are indicated by subscript “$i$” and scattering angles by subscript “$s$”.

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