Assessment of Wind Turbines Generators Influence in Aeronautical Radars

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Abstract—Airspace surveillance radars are very sensitive to interferences. The presence of wind turbines can create problems to some telecommunication systems relying on line of sight communication. This work analyses the disturbance in the propagation of the signals created by the movement of the rotating blades. A model is developed to characterise the wind turbine from the radar viewpoint, using the radar cross section concept and the diffraction theory. A model to quantify the impact on primary and secondary radars was also developed. The models used to describe the most probable airplane positions are also presented. A simulator was developed to know the amount of interference caused by the wind turbines for various scenarios. Simulation results show a great impact created by wind turbines on a primary radar, up to 36.05 dBsm. The results also show some critical points identified for the secondary radar, when the airplane lies in the same azimuth as the wind turbine. The Doppler shift could generate false targets in primary radar, due to the high velocities at the blade edge, up to 282 km/h. Finally, one defines exclusion regions around the radar, which can go up to 13 km, depending on the surrounding terrain and the radar characteristics.

Index Terms—Diffraction, Exclusion Regions, Interference, Primary Radar, Secondary Radar, Wind Turbine.

I. INTRODUCTION

Renewable energy sources gained an increased importance in the last years, and wind turbines generators in particular became very popular as a source of electrical energy. Given their own requirements, these wind generators are located on the top of hills, which may create problems to some telecommunication systems relying on line of sight communication. The movement of the metallic rotating blades may originate a significant disturbance in the propagation of the signals, hence, creating interferences. Ground-to-aircraft communication systems, and radars in particular, are very sensitive to interferences, which means that this disturbance needs to be looked at, quantified, and mitigated. A way to avoid problems is to create an exclusion region around the radar location (i.e., regions within which wind turbine generators are not allowed). NAV Portugal E.P.E. has several of these systems, being desirable to perform an analysis of the current performance, and to study solutions and design rules for these problems.

If wind turbines are in LoS with the radar, the amount of interference depends on the wind farm characteristics, as well as on the number of wind turbines, on their distribution by the wind farm, on the tower height, on the rotor and, consequently, on the blades position. The clutter frequency can change due to the blades rotation, a phenomenon known as Doppler Effect. The wind turbine Radar Cross Section (RCS) is used to quantify the amount of influence on radar, being a measure of how detectable an object is to a radar [1].

The impact of wind farms on radars is different for Primary Surveillance Radar (PSR) or for Secondary Surveillance Radar (SSR), because the first one leads with a 2-way path loss unlike the second, which by being cooperative, has a bidirectional communication [2].

It is not possible to develop universal guidelines that can be applicable in all scenarios for prescribing a minimum separation between wind farms and radars. However, it is possible to establish conservative estimates on the minimum separation between wind farms and radars, based on nominal assumptions about the wind turbine RCS, the radar transmit power, the sensitivity to interference, and the propagation conditions. The LoS distance is the most conservative estimate of the minimum separation necessary between the wind farm and radar, where the radar performance degradation is not expected under ordinary circumstances. Additionally, this LoS conservative estimate can be further reduced by taking into account other mitigating factors such as terrain shadowing, blockages, and the strength of wind turbine clutter returns [3].

Eurocontrol, [2], establishes four regions to make the assessment, the first, is the safeguarding zone, with 500 m, defining the area around PSR, and SSR, where no wind turbine should be placed. Zone 2 is the detailed assessment zone, 15 km for PSR and 16 km for SSR. Zone 3 is defined as the simple assessment zone, only applicable to PSR to all the wind turbines further than 15 km but in LoS. The zone 4 is the accepted zone, where the wind turbine impact in radars is tolerated.

[3] provides recommendations for assessing the influence on surveillance systems, where the results of a study exploring the effects of power reducing wind turbines on Federal Aviation Administration (FAA) radars are described. The criterion used to assess the impact on PSR is based on the...
increasing of effective noise floor that could cause desired targets to be lost or generate false targets. This report also concludes that the effects of wind turbines on SSR are not expected to differ from those of static structures.

The reports presented by Gavin Poupart, [1] and [4], analyse the impact that different designs of wind turbines produces on PSR and SSR, respectively, using computational models to assess this impact, which includes the wind turbine CAD model. He also analyses and compares the wind turbine echoes for different wind turbine yaw, and pitch angles. The report concludes that the impact of wind farms can be mitigated by a properly choose of the site, and by choosing materials that absorbs radio frequency waves. Other reports addressing the problem are studies carried out for real environment, as presented by Sean Yun, [5], that assess the impact of Riviera wind farm on MSSR at Kingsville naval air station.

David Jenn and Cuong Ton discuss in [6] many methods to predict the wind turbine RCS, citing their advantages and disadvantages. They present the difference between the rigorous and the approximated methods for calculate the wind turbine RCS. The report also shows the bi-static and mono-static RCS for two wind turbine configurations, a vertical axis three-blade design and a vertical helical design.

Rashid in [7] presents the methods used to model individual turbine mono and bi-static RCS, using the standard simplified physical optics far-field RCS approximation of a cylinder. In order to validate the results the model was compared to the full physical optics model. On the other hand, Mishra in [8] also presents a numerical model for a theoretical analysis of the radar signature from a wind turbine based on the of the conducting or dielectric cylinder RCS models.

This work addresses this problem, aiming at quantifying the impact for various scenarios. The goal is to assess the influence of wind turbines generators in Portuguese aeronautical radars, and to define models for the definition of exclusion regions around radar locations by creating a program, implementing the models presented in Section II, to quantify the impact created by these identified wind turbines in the radar's vicinities.

In Section II, the PSR and SSR working mode are presented, giving an overview of their main characteristics, as well as the wind turbine characterization. Section III contains the models used to quantify the impact created by wind turbine and a brief description of the simulator. Section IV presents the simulation results. Finally, conclusions are shown in Section IV.

II. BASIC CONCEPTS

A. Primary Surveillance Radar

PSR is a Non-Cooperative Independent Surveillance system to track all targets. It determines the 2D position without reliance on aircraft avionics [9]. The PSR switches between transmitting and receiving rates using a duplexer, i.e., an electronic switch is used when a single antenna serves both transmission and reception, which imposes a maximum range of detection [10]. The antennas of most of the radar systems are designed to radiate energy in a one-directional beam that can be moved simply by rotating the antenna [10]. Usually, a PSR antenna has approximately 35 dBi of gain; the peak transmitted power can achieve values above 1.2 MW [11], depending on the desired range. The main lobe has an azimuth beamwidth of approximately 1.30°, and an elevation beamwidth of 4.5°. The received signal must have a minimal power of 108 dBm [12]. PSRs also have the capacity of tracking over than 1 000 targets per scan [13], and over than 90% of detection probability [14]. The usual bandwidth is about 1 MHz [3].

B. Secondary Surveillance Radar

There are two main types of SSR systems: sliding window, and, monopulse SSR (MSSR). Both use 1 030 MHz band for uplink interrogations, and the 1 090 MHz one for the downlink transmissions. The distance between the radar and the airplane is calculated by the time difference between the interrogation and the reply message [14]. The position is updated on every radar sweep. The SSR ground station sends an interrogation message, and the aircraft replies to it using its transponder unit [15]. The interrogation standard (also called uplink format) consists in two pulses (P1 and P3) of 0.8 μs width, separated by a certain time that determines the interrogation mode [10].

The purpose of the P2 pulse is to allow the transponder to determine whether the interrogation was received from the main beam or, from a side lobe of the SSR radiation pattern. A reply to a side-lobe interrogation would give the controller a wrong airplane position. For this reason, Side-Lobe Suppression (SLS) is used to inhibit the transponder's reply in response to a Side-Lobe Interrogation (ISL) [16]. The transponder reply signal (SSR downlink format) is composed of a series of pulses.

MSSR also measures the azimuth in the ground using the differential beam, added to the existing one. The position is calculated using the signal amplitude received from both beams [17]. The introduction of monopulse techniques allows to reduce to one the number of replies per scan, reducing the congestion of band [18]. Typical values for SSR antenna are a gain of 27 dB; a horizontal beam width at -3 dB of 2.5°; a transmitted power ranging between [1, 1.5] kW; an elevation up to 45°; a range up to 250 NM; and, a sensitivity of 85 dBm [19]. The standard civil transponder have a transmitted power of 24 dBW and a sensitivity of -74 dBm; the antenna is omnidirectional and has 0 dB gain [20]. The typical secondary radar at -3 dB bandwidth is 6 MHz [21].

C. Wind Turbine Characterization

To produce electric energy using wind turbines the wind must have a speed between [2, 20] m/s [22]. Ideally, wind farm sites are on high and exposed land, in order to access to high wind speed [22]. Usually, wind turbines are grouped into groups that can go up to 10 turbines, forming a wind farm [22]. A wind turbine has three main parts, the tower, the blades, and the nacelle, this last being the place where the generator is located [1]. The wind turbine towers in Portugal usually have between [40, 100] m of height [23]. High towers mean more electricity produced, and with the height, the wind
becomes more stable and less irregular [22]. The tower is cone-shaped, with the base diameter longer than that on the top where the nacelle is positioned; the tower base diameter is, for a 100 m tower height, 4.2 m [24]. The usual wind turbines have three blades with a length up to 45 m, the relation between the tower height and the rotor diameter is about 1 or 1.2 [25]. The usually turbines nacelle rotates, to be transversal to the wind, in order to obtain the maximum wind energy [22]. The blades speed decreases when their diameter increases, the extreme cases analysed are 34 RPM for a 44 m rotor diameter, and 13 RPM for a 100 m rotor diameter [26].

III. THEORETICAL MODELS

A. Propagation Models

The first model to be taken into consideration is the LoS between the radar and the wind turbine, if the distance is greater than the LoS, then the effects caused by the structure should be tolerated. Thus, LoS methodology represents the most conservative criterion to do not anticipate any adverse effects on radar because uses the 4/3 smooth, round Earth and with no terrain effects. However, scenarios like those described before are unusual, because terrains are commonly irregular. Therefore it is necessary to examine the terrain surrounding the radar for potential shadowing effects mitigating any effect of the wind turbine on radar, by using a terrain database [3]. The knife-edge model is used to calculate the attenuation due to an obstruction caused by an obstacle between the radar and the wind turbine, [27], and the Daygout terrain database [3]. The knife-edge model is used to calculate mitigating any effect of the wind turbine on radar, by using a surrounding the radar for potential shadowing effects between the radar and the wind turbine, [27], and the Daygout terrain database [3]. The knife-edge model is used to calculate mitigating any effect of the wind turbine on radar, by using a surrounding the radar for potential shadowing effects between the radar and the wind turbine, [27], and the Daygout terrain database [3]. The knife-edge model is used to calculate mitigating any effect of the wind turbine on radar, by using a surrounding the radar for potential shadowing effects between the radar and the wind turbine, [27], and the Daygout terrain database [3].

1) Tower

In report [7] a simplified and approximate model has been developed to compute the mono-static and bi-static RCS of the tower. The bi-static RCS of each tower section was obtained using standard simplified physical optics far-field RCS approximations of a cylinder and it is given in (1). It is assumed that the ground is not illuminated in a significant way (in order to respect the RCS principles of plane wave on far field region).

\[ \sigma_{tower[m^2]} = k_{[m^{-1}]}^2 \Gamma \text{avg}[m] h_{visible}^2 \text{[m]}^2 \left( \Gamma \text{sinc}^2(\Theta) \right) \] (1)

in which:

\[ \Gamma = \left( \frac{\cos^2(\varphi_{scat[rad]}) - \cos^2(\varphi_{inc[rad]})}{\cos^2(\varphi_{inc[rad]})} \right) \] (2)

\[ \Theta = \frac{k_{[m^{-1}]}^2 \eta_{[m]}^2}{\cos \left( \frac{\varphi_{inc[rad]}}{2} \right)} \left( \sin \left( \varphi_{inc[rad]} \right) + \sin \left( \varphi_{scat[rad]} \right) \right) \] (3)

where:

- \( k = 2\pi/\lambda \) is the wave number;
- \( \lambda \) is the wavelength;
- \( r_{av} \) is the average radius of each cylindrical section;
- \( h_{visible} \) is the tower height;
- \( \varphi_{inc} \) is the vertical incident angle;
- \( \varphi_{scat} \) is the vertical scattering angle;
- \( \theta_{scat} \) is the bi-static scattering angle \( \in [-\pi, \pi] \).

2) Blades

The report [8] presents a first-order theoretical model of the radar signature produced by a wind turbine on S-Band radars [2, 4] GHz, which includes the PSR. According with the Canadian Standards Association Standard, [29], the wire for the purpose of lightning protection must have at least 4 mm of radius [29]. To model the radar return from a wind turbine, each blade can be assumed to be a cylinder of length \( L \). Furthermore, for the PSR operating frequencies, the scattering regime for the lightning wire is optic [8]. The RCS of a single wind turbine can be formulated by modifying the RCS models of the conducting or dielectric cylinder [8], such that it also incorporates the number of blades, the rotational speed and the dimensions of the wind turbine. The highly conducting thin cylinder assumption is given by (4), while (5) assumes the thin dielectric cylinder.

\[ \sigma_{cond(t)[m^2]} = \sum_{n=1}^{N} \pi L_{[m]}^2 \sin^2 \delta \sin^2 \delta \cos \left( \frac{2\pi \left( n - 1 \right)}{N} \right) \] (4)

\[ \sigma_{die(t)[m^2]} = \sum_{n=1}^{N} \pi L_{[m]}^2 \left( k_{[m^{-1}]}^2 \eta_{[m]}^2 \right) \left( \eta_{[-1]}^2 \right)^2 \sin^2 \delta \sin^2 \delta \cos \left( \frac{2\pi \left( n - 1 \right)}{N} \right) \] (5)

in which:

\[ \Theta = \left( 2\pi f_{rot[s^{-1}]} \right) + 2\pi(n - 1)/N \] (6)

\[ \delta = \left( k_{[m^{-1}]} L_{[m]} \right) \cos \left( 2\pi f_{rot[s^{-1}]} \right) + 2\pi(n - 1)/N \] (7)

where:

- \( N \) is the number of wind turbine blades;
- \( f_{rot} \) is the blade rotation frequency;
- \( L \) is the length of the turbine blade;
- \( \alpha \) is the radius of the cylinder (it is assumed 4 mm);
- \( \eta \) is the dielectric refractive index (usually 2.7 for solid fibre-glass).

The equations above assume that the plane of rotation of the wind turbine blades is the same as the radar signal. However, in general, this may not be the case. Assuming that the elevation of the wind turbine with respect to the radar is \( \gamma \), and the angle between the radar’s LoS and the wind turbine rotor rotation plane is \( \alpha \), the required transformation in the models above will be [8]:
\[ L_{ef} = L \cos(\alpha_{[\text{rad}]}) \cos\left(\gamma_{[\text{rad}]}\right) \]  

(8)

where:
- \( L_{ef} \) is the effective blade length.

C. Diffraction on Wind Turbine Blades

It is necessary to have a model to describe the impact of the blades on a bi-static situation; the primary and secondary radar wavelength is much smaller when compared with the wind turbine blade diameter and length. Therefore, it is possible to consider the blade edges as infinite edges, and, then, apply the Geometrical Theory of Diffraction (GTD). The GTD is an extension of Geometrical Optics (GO), which accounts for diffraction. It introduces diffracted rays in addition to the usual rays of GO. These rays are produced by incident rays which hit edges, corners, or vertices of boundary surface [30]. The initial value of the field on a diffracted ray is obtained from certain canonical problems, and can be computed as follows [30]:

\[ D_{\text{edge}} = m / 2 \]

(9)

\[ A = \left( \theta_{\text{incid}} - \alpha_{\text{diff}} \right) / 2 \]

(10)

\[ B = \left( \theta_{\text{incid}} + \alpha_{\text{diff}} \right) / 2 \]

(11)

\[ \alpha = \frac{2 \pi L}{2 \pi R_{[\text{m}]} \sin(\beta_{[\text{rad}]})} \]

(12)

where:
- \( \beta \) is the angle between the incident ray and the edge;
- \( \theta_{\text{incid}} \) is the angle between the incident ray and the normal to the blade;
- \( \alpha_{\text{diff}} \) is the angle between the diffracted ray and the normal to the blade.

Each wind turbine blade has two edges, and can be taken as parallels, therefore, the diffraction coefficient for the entire blade, \( D_{\text{blade}} \), can be assumed as:

\[ D_{\text{blade}} = 2 D_{\text{edge}} \]

(13)

D. Impact on PSR Performance

If a wind turbine falls into the radar LoS, then, it is possible that scattered energy from the wind farm could adversely affect the performance of the radar receiver by increasing its effective noise floor level. The occurrence of such increased noise could cause desired targets to be lost, or could possibly even cause false targets to be generated. The criteria that can be used to assess a threshold for this effect, given in [3], is the following:

- a power level of scattered energy that is less than -9 dB relative to the radar’s noise floor (i.e., an Interference-to-noise (I/N) level that is equal to or less than -9 dB) will not cause adverse effects;
- an I/N level that is less than or equal to -6 dB will cause few effects;
- levels higher than -6 dB may cause measurable losses in desired targets and could cause the generation of some false targets.

The clutter strength is given by (14) and the calculation of the radar receiver’s sensitivity is given using the thermal noise level equation [3].

\[ P_{\text{R}} = \frac{P_{\text{R,primary}}[\theta, \phi] G_{\text{r}}(\theta, \phi) \sigma^2 \rho_{\text{m}^2}}{(4\pi)^3 a_{\text{rad}}^3 [\text{m}^4]} \]

(14)

where:
- \( P_{\text{R}} \) is the received power;
- \( P_{\text{R}} \) is the transmitted power;
- \( G_{\text{r}}(\theta, \phi) \) is the transmitted gain for a given direction;
- \( G_{\text{r}}(\theta, \phi) \) is the received gain for a given direction;
- \( \sigma \) is the wind turbine radar cross section;
- \( d_{\text{rw}} \) is the distance between the radar and the wind turbine.

The scattered energy, due to the effect of the time varying blades RCS, could, in certain times, exceed the threshold power. Consequently, in these moments, the wind turbines will appear in the radar display, so it is desirable to know the probability of the scattered energy being above the threshold power and getting caught by the radar. Therefore, using (14) the time that is exceeded can be computed as follows:

\[ P_{\text{R,blades}}(t) + P_{\text{R,primary}}[\theta, \phi] - P_{\text{R,primary}}[\theta, \phi] = 0 \]

(15)

\[ p_{\text{clutter}} = \frac{p_{\text{threshold}}[\theta, \phi]}{p_{\text{primary}}[\theta, \phi]} \]

(16)

where:
- \( p_{\text{clutter}} \) is the probability of the scattered energy be above the threshold;
- \( p_{\text{threshold}} \) is the period of time in which the scattered energy is above the threshold;
- \( p_{\text{primary}} \) is the wind turbine rotation period.

Furthermore, \( p_{\text{clutter}} \) does not represent the exact probability of a wind turbine appear in the radar display, because, due to the radar rotation, the radar is not always pointing to the turbine, and also owing to the tight horizontal beam width, therefore, the period of time that, at least, half power is transmitted to the turbine can be computed as follows:

\[ \tau_{\text{illumination}} = \frac{\tau_{\text{radar}}[\theta, \phi]}{2\pi} \]

(17)

where:
- \( \tau_{\text{illumination}} \) is the period of time that the radar is pointing to the wind turbine;
- \( \tau_{\text{radar}} \) is the radar revolution time;
- \( \alpha_{\text{H,3dB}} \) is the horizontal half power beam width.

Consequently, the probability of the radar being pointing to the wind turbine, \( P_{\text{radar}} \), is:

\[ P_{\text{radar}} = \frac{\tau_{\text{illumination}}[\theta, \phi]}{\tau_{\text{radar}}[\theta, \phi]} \]

(18)
Finally, the probability that a wind turbine has to appear in the radar display, $p_{\text{tracked}}$, is given by:

$$p_{\text{new}} = p_{\text{before}}(1 - p_{\text{tracked}})$$  \hspace{1cm} (19)$$

where:
- $p_{\text{new}}$ is the new probability of detection;
- $p_{\text{before}}$ is the probability of detection without wind turbine.

**E. Impact on SSR Performance**

Reflections from the wind turbine can affect the SSR operation for an aircraft in its vicinity. Depending on the time difference between the direct and reflected signals, and on the strength of the wind turbine reflections, the possible problems that could occur are split into two categories. The first is when the reflected and the direct signal cannot be separated by the receiving system. This can lead to problems such as:
- position errors;
- fading (a reduction in signal strength).

The second category of effects occurs when the reflected signal can be separated from the direct signal, i.e., if the reflected signal is strong enough to create a false target report, or to corrupt the code of the SSR signal [4]. The false target or false response reports are due to the implementation of ISLS, or to corrupt the code of the SSR signal [4]. The false target or reflected signal is strong enough to create a false target report, if the difference between the direct and reflected signals is lower than a given threshold position, errors may occur.

In order to compute SIR, one must know the power level received by the aircraft via direct path, and the power level received via reflected path. The power received via direct path, using the free space propagation can be computed as follows [27]:

$$p_{\text{direct}[W]} = \left(\frac{\lambda}{4\pi d_{\text{direct ray}[m]}}\right)^2 p_{\text{[W]}}(1, \varphi)G_r(1, \varphi)$$  \hspace{1cm} (20)$$

where:
- $d_{\text{direct ray}}$ is the direct distance between the radar and the airplane.

To compute the power level via reflected part, one must consider the power that comes from the tower, coupled with the power that comes from the three blades. Therefore, the power diffracted on the wind turbine tower, using (1) to compute the RCS, can be calculated as follows [2]:

$$P_{\text{tower}[W]} = \frac{p_{\text{[W]}(1, \varphi)G_r(1, \varphi)}^2 ||\vec{\text{tower}}|^2 d_{\text{tower}[m]}^2}{(4\pi)^2 d_{\text{tw}[m]}^2 ||\vec{\text{tw}}|^2 d_{\text{rw}[m]}^2}$$  \hspace{1cm} (21)$$

Then, the power diffracted on each wind turbine blade is given by [31]:

$$P_{\text{blade }i[W]} = \frac{p_{\text{[W]}(1, \varphi)G_r(1, \varphi)}^2 ||\vec{\text{blade }i}|^2 d_{\text{blade }i}^2}{16\pi^2 d_{\text{rw}[m]}^2}$$  \hspace{1cm} (22)$$

where:
- $i$ is an index that represents each blade.

As shown in Fig. 1, the total interfering power for each wind turbine ($I_{\text{WT}_n}$) is the sum of the power that comes from each blade and from the tower, as follows:

$$I_{\text{WT}_n[W]} = P_{\text{tower}[W]} + \sum_{i=1}^{2} P_{\text{blade }i[W]}$$  \hspace{1cm} (24)$$

The SIR for a wind turbine $n$ must be computed as follows:

$$\rho_{1,n} = \frac{P_{\text{direct}[W]}}{I_{\text{WT}_n[W]}}$$  \hspace{1cm} (25)$$

where:
- $\rho_{1,n}$ is the SIR at the receiver.

In order to ensure that the interfering power will not affect the correct operation of the radar, one must guarantee the SIR above the minimum SIR required at the receiver.
F. Doppler Effect

Other impact in Air Traffic Control (ATC) radars performance is the Doppler Effect, which consists on compression or expansion of signals frequency by a moving object, the frequency shift is computed as [1]:

$$f_d[\text{Hz}] = \frac{2v_R}{\lambda_{[\text{m}]}}$$

(28)

where:
- $f_d$ is the Doppler shift;
- $v_R$ is the radial velocity.

After being computed the frequency shift created by the wind turbine, it is crucial know the tolerance of the radar to those shifts. Therefore, for the primary radar, the requirement for the frequency tolerance is [32], for a radar operating in the frequency bands between [2 700, 9 500] MHz, 1 250 ppm.

For the secondary radar, the tolerance must be differentiated between the uplink and the downlink cases. Therefore, the requirements for the frequency tolerance are [33] ± 0.2 MHz for the uplink, and, ±3 MHz for the downlink.

G. Simulator Description

In order to analyse the influence caused by the wind turbines on ATC radars, a simulator was created with the models above described. This simulator estimates the amount of interference produced by the wind turbines for different airplane positions. As explained before, the influence of the interference is different for the two types of radars analysed. The main goal of this simulator is to analyse all the interfering scenarios, for the different airplane routes, and to identify wind turbines that may cause measurable interference, and, with these results estimate the exclusion regions. This simulator allows to analyse the interference created by future new scenarios that can appear, as new radars or new wind turbines.

IV. RESULTS ANALYSIS

A. Doppler Effect Impact Assessment

Three different scenarios were identified to analyse the Doppler Effect impact created by the wind turbines on ATC radars, namely, the variation of rotor angle in relation to radar, the variation of the blade length, and the variation of the rotation speed. The two extreme cases were analysed:
- the 44 m rotor diameter, with a maximum rotation speed of 34 RPM;
- the 100 m rotor diameter, with a maximum rotation speed of 13 RPM.

For the secondary radar, the highest value for the Doppler shift is 569.1 Hz, for the 22 m blade, in the downlink, and for a rotor rotation of 90°. As previously presented, the tolerance for the frequency deviation is 0.2 MHz for the uplink, and 3 MHz for the downlink, therefore, the $5.69 \times 10^4$ MHz computed for the Doppler shift is far below from these values. For the primary radar, the highest value is 1 483 Hz, for the 22 m blade, and for the 2 840 MHz radar frequency, and also for a rotor rotation of 90°. The tolerance for the frequency deviation is 1 250 ppm, which means that, for the 2 760 MHz the tolerance is 3.45 MHz, and, for the 2 840 MHz the tolerance is 3.55 MHz. The results obtained for the frequency shift allow to state that the Doppler shift produced by wind turbines will not be a problem for the radar signals reception viewpoint, because the tolerance values are never exceeded. However, for the PSR operation, and due to the high radial velocity at the blade edge, the frequency shift produced can be similar to an aircraft, therefore, the MTI can recognise as a target, showing the wind turbine in the display.

B. Interference Results

1) Primary Radar

NAV Portugal has only one PSR located in Lisbon airport. First, two tables are presented for one tested scenario, in order to compare the maximum and minimum received power for the different possibilities, i.e., for different blades material, for different radar operation frequency, and for different wind turbine orientations, to understand the influence of these parameters on the results. A wind turbine in Almargem was chosen, without terrain attenuation. Table I and Table II shows the simulation results. The North-Nothwest (NNW) is the prevailing winds orientation for Portugal.

<table>
<thead>
<tr>
<th>WT Orientation</th>
<th>Maximum received power [dBm]</th>
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<tr>
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<tr>
<td>Radar</td>
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<td>-48.17</td>
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<td>NNW</td>
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<tr>
<td></td>
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<tr>
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<td>-41.96</td>
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<td></td>
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<td>-51.31</td>
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In relation to the blades materials, it is noted that for the maximum received power, the difference between metallic blades and dielectric blades is always below than 1 dB. For the minimum received power, there is no difference between the materials used. Regarding to the radar operation frequency, it...
can be observed that the difference between the 2 760 MHz and 2 840 MHz bands is quite high, reaching, in some cases, values above 10 dB. Finally, regarding the impact of the wind turbine orientation in the received power, it is shown that, for the metallic blades at 2 760 MHz operation frequency, the difference is around 3 dB, which means twice the received power when the wind turbine is pointing to the prevailing winds. For dielectric blades, the orientation leads to a difference over than 8 dB. The difference in the received power due to the orientation is around 3 dB, when the radar operates at 2 840 MHz.

Simulation results show that the scattered energy for almost all the wind turbines causes always interference to the radar, because it is always above the radar threshold. It was observed that these wind turbines are in LoS, which means that there is no terrain attenuation between the radar and the wind turbines. The wind turbines identified are at a distance between [12.62, 15.56] km, and cause a maximum radar received power between [-37.95, -28.60] dBm, and a minimum received power between [-37.26, -57.71] dBm. The turbines are placed in the azimuth between [-53.5, 8.5]° in relation to the North, therefore, the degradation in the radar performance can occur in this azimuth interval. The wind turbine RCS is between [27.67, 36.05] dBSm. About 51.7% of the wind turbines produce more scattered energy when the radar operation frequency is 2 760 MHz, and, the remaining 48.3%, when the radar operation frequency is 2 840 MHz. The worst blade material is usually the dielectric, but the difference in relation to the metallic blades is very short, less than 1 dB. The usual orientation that leads to a higher received power is NNW, however, note that the values obtained are the peaks, it does not mean that the dielectric blades, or the orientation to the NNW, lead to a higher average scattered energy.

Some turbines in Sardinha’s wind farm only cause interference to the radar sometimes. With terrain attenuation, it is noted that the minimum received power decrease significantly, going below than receiver threshold. Note that the terrain attenuation affects the signal twice, because it is a PSR signal. For these cases, it is interesting to know the probability of interference. The probability of the scattered energy being above the threshold is, for the first four wind turbines, about 48%, for the last wind turbine is 99%. These values represent a decrease of the detection probability of 0.2%, and 0.4%, respectively. The strong variations between the minimum and maximum received powers due to the blade rotation will appear as flashes in the radar screen. Consequently, this amount of scattered energy will cause an increase in the radar’s detection threshold, in the resolution cell where the wind turbine is located [2].

From the simulations, it can be stated that the presence of wind turbines could affect the radar operation in the same azimuth where they are, therefore, the probability of detection can be compromised in these azimuths.

2) Secondary Radar

There are two different possibilities of a wind turbine produce interference in a secondary radar, the first one is when the radar boresight is pointing to the airplane, and the second one is when the radar is pointing to the turbine. As expected, when the radar is pointing to the airplane, the direct received power is far above the interfering power. However, when the radar is pointing to the turbine, and due to the high directivity of the radar antenna, the received power is below than the interfering power. Therefore, for the first case, the SIR is above the two thresholds, and for the second case, the SIR is below the thresholds. Moreover, the second case not creates interference problems due to the ISLS implementation.

The values obtained for the SIR are very high; therefore the probability of decreasing below the thresholds is very low. Moreover, the chance of the wind turbines causing more interference is when they are in the same azimuth as the airplane path, because in this situation, the horizontal gain in both directions is similar. Consequently, as above described, when the radar is pointing to the airplane, for the case when the wind turbines do not lay in the airplane route, the SIR is always above than the receiver threshold.

The impact of wind turbine be pointing to the prevailing winds (NNW), as expected, when the wind turbine is oriented to another direction than the orientation that leads to a maximum interfering power, the SIR is higher. Moreover, the larger the angle between the maximum of the diffraction and orientation to NNW, the smaller the diffraction coefficient, and, consequently, the interfering power. The general SIR behaviour is the same for both the received powers, changing only the diffraction coefficient value.

It was also analysed the impact of different Flight Routes (FR) and different Flight Levels (FL) on received SIR. The worst FL is the highest one, the FL 300, this fact is mainly due to the radar vertical diagram, because, for the higher FL the gain in the airplane direction is low and in the wind turbine direction is high, therefore, it will lead to a lower SIR. The worst FR is the one that is in the same wind turbine azimuth, due to the narrow radar horizontal radiation pattern.

The minimum received SIR is always for the downlink case, mainly due to the diffraction coefficient, and, because, in the downlink, the whole turbine is visible.

The worst interference result was occurred for the wind farm in Joguinho North, with five interfering turbines at 10 km from the radar. The turbines are in LoS, and the worst route for this wind farm is FR 218. This route has approximately the same azimuth as the wind farm, in relation to the radar. The worst point is at 84 km from the route initial point, which corresponds to a point where the wind farm and the airplane lay in the same azimuth, and, therefore, the gain is nearly the same for both. In this case, the interfering power achieves a maximum value, being the SIR 20.42 dB. Moreover, Fig. 3 shows the SIR behaviour for this case, using 100 m of airplane path interval, instead of 1 km, in order to have more resolution. It can be seen a peak in the received SIR, reaching almost the conservative threshold. The geometry of this worst case is shown in Fig. 4, the red label marks the radar, at above in the right side, at below marks the airplane critical point, and, in line between both is the wind farm. Note that this simulation has no sufficient resolution to affirm that near this
point, the SIR does not cross the thresholds. Moreover, due to the signal fading it is not possible to state that this point is not critical, and not causes interfering problems.

Figure 3. SIR for the worst simulation result, for FR 218 and FL 10

Figure 4. Geometry for the worst simulation result, for FR 218 and FL 10

C. Exclusion Regions

1) Primary Radar

In the definition of an exclusion region for the PSR, two different types of analysis can be adopted:

- assuming flat terrain, and the highest value observed for the RCS, it is possible to know the minimum distance;
- assuming a minimum terrain attenuation which allows to tolerate the wind turbine presence.

For the application of the method applied for the flat terrain, the highest value for the RCS that has been calculated is used, i.e., 36.05 dBsm. Applying (14), and using the radar power threshold of -106 dBm, it gives an exclusion region around 200 km. It is obviously that this is impossible to implement, this high value is mainly due to the very high transmitted power, and also due to the high transmitted and receiver gains. For the considered interfering regions (16 km), the scattered energy is always very high, due to these factors but also due to the high wind turbine RCS. Other method to decrease the amount of scattered energy is take into account the terrain attenuation, therefore, to guarantee that the received power is below the receiver threshold the, terrain attenuation must be, for the worst case simulated, 77 dB, which is a huge value, however, the PSR signal is two-way, therefore, it is just necessary 38.5 dB for each signal side. The frequency 2 840 MHz will lead to a higher value for the terrain attenuation, due to the frequency dependency on the attenuation computation.

In order to overcome that situation, and because MTI can confuse the wind turbine Doppler signature with an aircraft, the radar must have a signal processing to reject the clutter coming from a wind farm. The most used is the spectrum filters, which is a solution that is based on modifying their existing radars by incorporating a software based spectrum filter, which compares between the target and the wind turbine Doppler signatures [34]. This solution is easy to implement and can be rolled out to all radars of the same type without replacing to new equipment. Another solution is use Adaptive MTI (AMTI) techniques, which not only filters out the fixed clutter, but also estimates the predominant Doppler value of the remaining, moving clutter in each resolution cell [34].

2) Secondary Radar

In order to create the exclusion regions for the secondary radars, the airplane position must be coincident with the wind turbine, in relation to the radar, to create the maximum interference. This situation is critical, because the gain in the horizontal direction is the same for the turbine and for the airplane. A route which simulates the SIR for all these possible critical points was defined. Moreover, different FL generates different interference powers coming from the turbine, therefore, it is necessary define different exclusion region for the different FL.

The exclusion region is different for each radar, due to the different location, height, terrain around the radar and the tilt. To define the exclusion region, the values for the higher wind turbine were used. The FR used is the one that have more wind turbines in their azimuth, and, in the cases where there are no wind turbines, the route that has lower terrain attenuation was chosen, in order to have the maximum interference. From the radar point of view, it is assumed an equally exclusion region around the radar, and it is just necessary to know the maximum distance from the radar where no wind turbines should be placed. The first analysis is for a wind turbine at 1 km from the radar, and the distance increases progressively. For the test, just one wind turbine was considered.

Fig. 5 shows the evolution of SIR for the different FL, in function of the wind turbine distance to the radar. Fig. 5 also shows that the two lower FL have a received SIR far above the higher FL. This fact is mainly due to the radar vertical gain variation. As previously described, this type of radar is very directive, therefore, for the upper FL, the gain in the airplane direction is lower, and, consequently the SIR is lower too. The black line in Fig. 5 represents the minimum SIR, which is the threshold for the definition of the exclusion regions, 10 dB.

It is possible to conclude that the SIR, and, consequently, the exclusion region is strongly affected by the surrounding terrain. The peaks of SIR that can be seen in Fig. 5 are due to the terrain depressions presented in Fig. 6. For those points the terrain attenuation degrades the interfering power that comes
from the turbine, and, consequently, the received SIR is higher. For example, it is possible to observe a deep terrain obstruction at 4 km, 8 km and 16 km, therefore, a wind turbine located in these points is in non LoS, so, the interfering power created is lower, and, the SIR will increase.

For the lower FL the exclusion region is lower too, this is mainly due to the radar directivity, as explained before. The worst exclusion region, 13 km, was obtained for the P. Santo radar for the highest FL (FL 300), this is mainly due to the smooth surrounding terrain, and, the entire wind turbine becomes in LoS. Moreover, the radar is not in a higher position in relation to the island, and the radar has a tilt of -1°, therefore, the wind turbine is always located in the radar main boresight, producing a higher interfering power.

The Table III summarises the exclusion regions for all the secondary radars in Portugal.

<table>
<thead>
<tr>
<th>Radar</th>
<th>Exclusion Regions [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FL 10</td>
</tr>
<tr>
<td>Lisbon</td>
<td>2</td>
</tr>
<tr>
<td>Porto</td>
<td>1</td>
</tr>
<tr>
<td>Faro</td>
<td>1</td>
</tr>
<tr>
<td>S. Maria</td>
<td>2</td>
</tr>
<tr>
<td>P. Santo</td>
<td>2</td>
</tr>
<tr>
<td>Foia</td>
<td>1</td>
</tr>
<tr>
<td>Montejunto</td>
<td>1</td>
</tr>
</tbody>
</table>

For the Secondary Surveillance Radar (SSR) analysis, the impact in the received Signal-to-Interference ratio (SIR) was simulated, for the radar pointing to the turbine, and, for the radar pointing to the airplane. It was also simulated the impact of wind turbine pointed to the prevailing winds (NNW), in comparison with the wind turbine faced to the radar, and it can conclude that the radar tilt and the position in relation to the turbine have a major role in the exclusion regions, especially for the higher FL. For example the radar in S. Maria and in P. Santo are in a higher position in relation to the turbines, however, the radar in S. Maria does not have down tilt, and, consequently the exclusion region is lower than P. Santo.

Using the exclusion regions computed above, it is possible to state the follows:

- The wind turbines located in Lisbon and Montejunto do not affect the SSR correct operation, because, they are outside the worst exclusion region.
- The P. Santo radar has 3 wind turbines within the exclusion region. The wind turbines are located at 4.55 km, therefore, they can produce measurable interference to an airplane in FL 150, and in FL 300.
- The S. Maria radar has also 3 wind turbines in their vicinity, located at a distance of 4.95 km. FL 150, and FL 300, can also compromises the radar correct operation.
- The 5 wind turbines in the Foia region are only at 2 km from radar; therefore, they can create measurable interference to an airplane in FL 150 and FL 300.
- The Porto, and Faro regions does not have wind turbines in their vicinities.

V. CONCLUSIONS

This work consists in the assessment of the impact created by the wind turbines on radars, differentiating the different types of surveillance radars used by NAV Portugal. A study was performed for each radar in Portugal mainland, in Azores and in Madeira. After the assessment, exclusion regions for those radars were defined.

The maximum Doppler shift occurs when the rotor is perpendicular to the radar. For the both analyzed cases, 44 m and 100 m of rotor diameter, the frequency deviation is not a problem for the radar signals reception viewpoint, because the tolerance values are never exceeded.

From the simulation results for the impact on Primary Surveillance Radar (PSR), on can conclude that there is no much difference (less than 1 dB) between the model used for metallic blades and the model used for the dielectric blades. On the other hand, the impact of the radar operation frequency can lead to differences up to 10 dB, therefore, the radar carrier of 2 840 MHz creates less scattered energy. For the turbines in the Lisbon region the maximum radar received power is between [-37.95, -28.60] dBm, which is a high value, far above the threshold, mainly due to the high values computed for the RCS which are between [27.67, 36.05] dBsm. These values for the wind turbines RCS are compliant with the maximum value provided by the EUROCONTROL. The usual orientation that leads to a higher received power is NNW. The terrain attenuation has a major role in the impact created by the wind turbines on PSRs, because affects the signal twice.
be concluded that when the wind turbine is faced to NNW, the received SIR is higher. It was also analysed the impact of different Flight Levels (FL) and Flight Routes (FR) on the received SIR, it can be stated that higher the FL, the lower the SIR is. The worst FR are those that are in the same azimuth as the wind turbine. It was observed that the SIR for the downlink is always lower than SIR for the uplink. For all the scenarios the computed SIR was always above the conservative threshold of 20 dB.

The computed exclusion region for PSR was around 200 km, or a terrain attenuation above 38.5 dB, in order to have values for the scattered energy below the threshold. For the interfering region (16 km) the scattered energy is always above the threshold, therefore, it is necessary to have a signal processing to reject the clutter coming from a wind farm, as implementing software based spectrum filters, or, using adaptive MTI techniques.

The exclusion region for the SSR was obtained using the simulations for the critical points, which are the situation were the airplane and the wind turbine lies in the same azimuth.

Therefore, it was tested the SIR for different wind turbines distances to the radar and for different FL. It was observed that the exclusion region is different for each radar because depends on surrounding terrain, the location, the height and the tilt. An equally exclusion region around the radar was assumed. It was observed that for the upper FL the exclusion region is higher, due to the radar directivity. It was defined an exclusion region between [1, 2] km around the radar for an airplane level of FL 10. For FL 55 the exclusion region increases up to 4 km, for the FL 150 the exclusion region ranges between [6, 9] km. Finally for the upper FL it was observed the maximum values for the exclusion region that can go up to 13 km.

REFERENCES