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INFLUENCE OF WIND FARMS ON THE EFFECTIVE OPERATION OF GROUND-BASED RADARS

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Abstract: *In the current international context, when the airspace must be permanently monitored, Romania, the NATO eastern border, faces new problems regarding the influence of wind farms on terrestrial radars. Near the conflict zone are large wind power plants, which sometimes can interfere with the terrestrial radars. The distance and direction of the monitored object are estimated by evaluating the produced echo. The transmitted radio frequency can be perturbed by a reflective object, such as wind turbine blades, in motion, for some orientations produced by the wind direction. Some elements regarding terrestrial radars, theoretical and experimental aspects, associated with the measurements' results, and a few conclusions are presented, to illustrate the possible influence of wind turbines on the airspace surveillance capacity.*
Key words:*, Experimental modeling, Mathematical modeling, Primary Radars, Secondary Radars, Wind power plant, Wind turbine.*

1. INTRODUCTION

Nowadays, due to global warming, the development of power plants based on renewable sources has become a necessity. In Romania, there is the largest onshore wind power plant in Europe at Cogealac-Fantanele, of over 600 MW, in Tulcea County, [1]. As a result of monitoring the wind and solar potential, Dobrogea and southern Moldova have proven to be favorable for the development of wind, and photovoltaic power plants. Due to the energy market liberalization in 2018, an increased interest in the public and private sectors for electricity generation based on renewable sources was recorded. Wind power plants are currently composed of 3-7 to hundreds of wind turbines, depending on the available land surface and the desired capacity to be installed. Due to the technical progress recorded in the last decades, wind turbines have frequently reached heights of over 120-160 m, with blades having lengths of 80-100 m and even more.

Romania represents the eastern border of the NATO alliance. Starting from February 2022, an armed conflict between Russia and Ukraine is registered in this area of Europe, with a direct border with Ukraine and a coastline on the Black Sea of over 200 km Romania must face new challenges. Due to the massive transport of grain by sea to the rest of Europe, due to the intense fighting that takes place in the ports area in Ukraine and the area of the Crimean peninsula, the Black Sea, and the Moldova region with its counties bordering the Republic of Moldova and Ukraine has become an area that must intensively be surveyed by air, land, and sea. The entire area is monitored with radar systems that allow the detection of any problems that may occur in air or marine space. Currently, there are many terrestrial radar systems installed and more systems will be purchased, more modern, more efficient, and with even greater coverage.

Besides, these military radar systems [2], it should be borne in mind that there are also terrestrial weather radars to warn of increasingly frequent critical phenomena, of strong storms and atmospheric instabilities. This year proved to be a year with large temperature variations and numerous phenomena of instability, with abundant precipitation and high wind gusts, with intense precipitations often accompanied by hail.

For some radar systems, the presence of wind turbines and the waves reflected by their rotors can affect the monitoring system, [3]. The number of turbines, their changing in orientation, and speed rotation determined by the wind direction and intensity, associated with their height, often represent technical challenges for the radars' efficiency. They must be carefully evaluated to establish an optimal position for each case and to ensure a good level of air and marine surveillance capacity. The influence of wind power farms on the effectiveness of terrestrial radar systems is analyzed for primary and secondary radars. The interference between the operation of wind turbines and radars depends on the types of radars existing in the area, military or meteorological. They should not be affected in their ability to fulfill the mission, for which they were installed, assuming it is necessary to create an exclusive protection zone, [4].

The radars use pulses of electromagnetic and radio frequency energy transmitted and received, reflected by a reflective object, usually a moving body. The blades of wind turbines can reflect some of this energy, called "echo." By evaluating the echo, radars - RAdio Detection And Ranging estimate the distance and direction of the reflecting object if there is no interference. Due to the increased reflective surface given by the moving blades of turbines, they can cause false targets on the primary radar. The radar's good operation can be affected if the highest point of the turbine is radio-horizontal for the primary radar. If the number of false targets generated by wind turbine reflections is too high, it may exceed the radar's processing capacity. Its operational capability suffers. Sometimes, the affected area depends not only on the position and orientation of the turbines' blades but also on the land configuration. Some theoretical aspects are presented, associated with some cases when the proper functioning of the primary and secondary radars is affected. A numerical model was created for a natural area under analysis near the Bacau airport, and some of the obtained results are mentioned. Finally, some possible solutions are presented to solve this problem based on flight test results.

2. RADAR CHARACTERISTICS AND THEIR PRINCIPLES OF OPERATION

Current international conditions require air, land, and sea surveillance to be as efficient as possible. On the other hand, global warming and the greenhouse effect determined the development of wind power plants in Romania, in the east of the country, considering its high energy potential in this area. There is currently a legal framework that mentions the rules for the location of wind power plants near the tracking infrastructure, which would allow the surveillance of the airspace, terrestrial, and marine navigation systems. The problem is that these two aspects interfere. On the one hand, we want to build as many wind power plants as possible in this part of the country but on the other hand, this area must be monitored more intensively due to the international situation that has arisen. The question is at what distance the performance of the radar sensor is significantly affected by the presence of high-capacity wind turbines in its vicinity, Fig. 1.

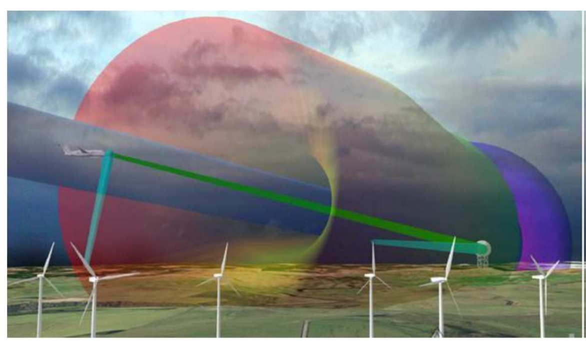

Fig.1. Operating system, radar, target, wind farm and areas of influence

The radar systems, regardless of their military or meteorological type, are composed of a sensor that uses electromagnetic radiation in the frequency spectrum, an antenna, a duplexer, transmitter, receiver, and a processor with a controller and display. Generally, the antenna is used for both transmission and reception, and the duplexer switches the direction of the signal between transmission and reception.

The tracking signal has the form of a set of short pulses sent into space by the antenna generated by the radar transmitter. The electromagnetic wave that reaches the tracked object (target) creates induced oscillations. The target reflects part of the electromagnetic energy in the radar direction, creating an echo signal in the radar antenna. It gives information about the target. Problems arise with the moving targets or when there are numerous targets in the radar's field of action, as is the case with several turbines in a wind farm whose rotors are in motion, Fig. 2.

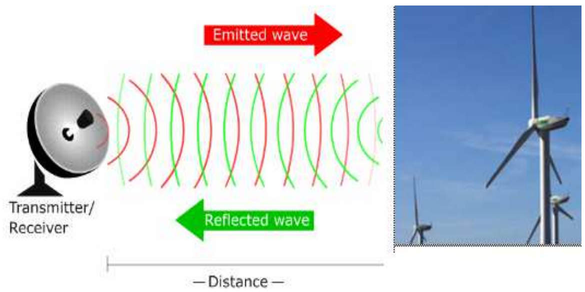

Fig.2. The operating principle of the radar

The processing of the echo signal depends on the emission power and the receiver power, on the ratio between the signal (direct wave) and the level of disturbances produced by other sources, called the signal/noise ratio, on the distance to the target, the effective reflection surface, which in the case of a wind farm increases in the case of a large number of high-power turbines, with large blades, the geometry of the antenna or some atmospheric phenomena. The radar also receives signals reflected by natural or artificial physical objects, for example, buildings, vehicles, and hills, but also electromagnetic radiation produced by antennas, mobile telephone masts, TV and radio, etc. The strength variation of the received signal can also occur due to the target movement or weather conditions, heavy rain, or hail. Obstacles in the direction of propagation reflect electromagnetic waves.

Due to the finite size and shape of the radar antennas, the output power is distributed as a lobe, Fig.3-a, b. The central, main lobe contains most of the received information. Near of it, the secondary and tertiary lobes can also radiate enough energy to introduce a disturbance into the system. Next, the main types of radars will be briefly presented.

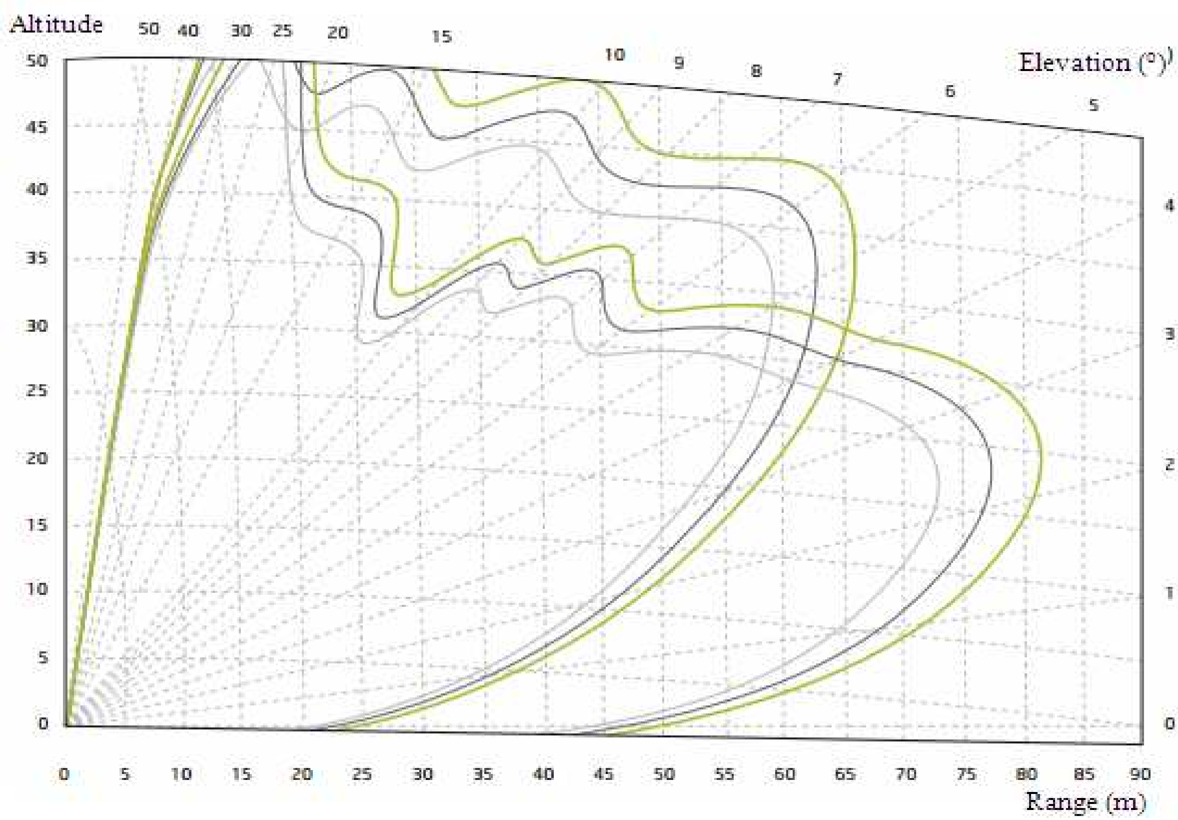

Fig.3-a. The main lobe: green-no interference, dark grey 10% interference, and gray 20% interference

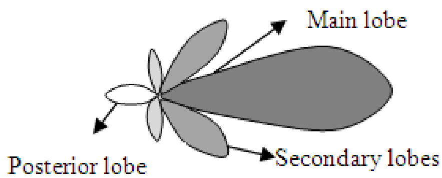

Fig.3-b. Structure: main, posterior, and secondary lobes

The main components of the radar are:

- The transmitter, which produces high-power and short-duration R_f-radio-frequency energy signals, in the monitored space;

- Duplexer, which alternately switches the antenna between transmitter and receiver, thus allowing only one antenna to be used. Switching is necessary because, in the case of high-power impulses from the transmitter, the receiver can be destroyed if a large amount of energy enters it;

- The receiver amplifies and demodulates the incoming R_f signals and provides video signals at the output;

- The antenna transfers the energy of the transmitter to the signals transmitted in space.

2.1 Primary surveillance radar-PSR

It is the most frequently used air defense radar that functions with active signal and passive response. It transmits R_f waves focused by the antenna to form the directivity characteristic. It depends on the type and shape of the antenna but also on its ability to rotate and swing. This type of radar activates completely independent of the target. Any action of an obstacle provides a returned signal. The antenna can rotate either in a sector of a few degrees or up to 360° to cover the entire airspace around the radar. Fig.4 shows such a 360° PSR coverage mode.

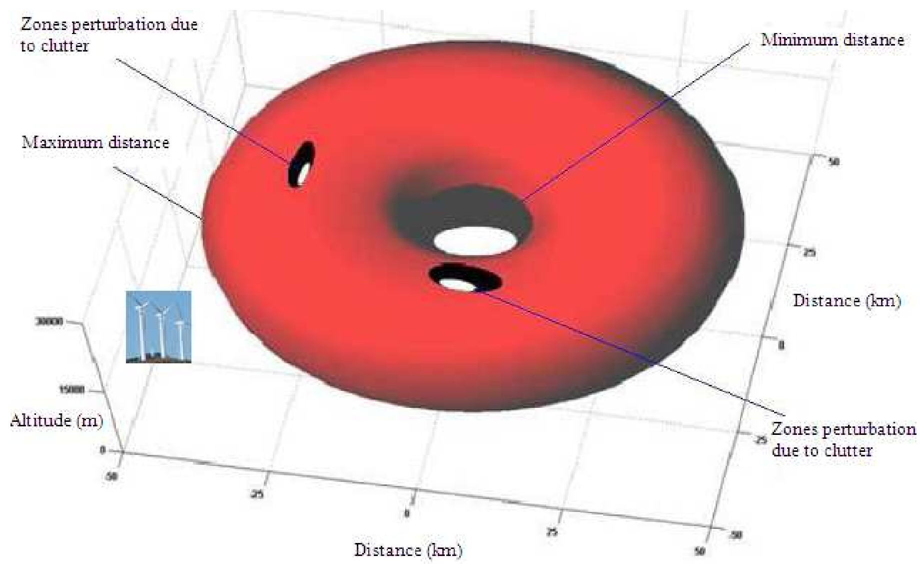

Fig.4. The spatial coverage of the radar

Most radar is designed to determine all parameters such as distance, azimuth, and height. They use multiple beams, as three-dimensional-3-D radars. Fig. 5 illustrates two different types of radars that form a multi-beam directivity pattern. The first one, Fig. 5-a, has several transmitters that form several over-lapping beams, of the type of 2-D radars with the antenna rotating to cover the entire airspace. The second, Fig. 5-b has phased arrays of antennas, with numerous transmitters and receivers forming the antenna.

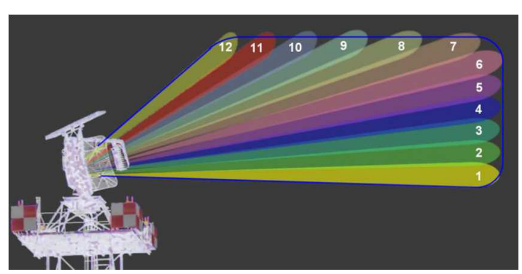

Fig.5-a. The directivity characteristics with stacked bundles

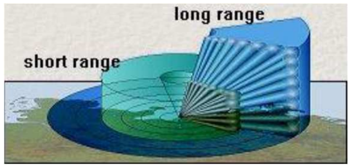

Fig.5-b. Directivity characteristics for phased array antenna

This radar allows electronic scanning of the directivity characteristic in the vertical plane by different phase shifts of the signals applied to each element. Rotating the antenna in azimuth makes it possible to cover the surveillance space. The main disadvantage of PSR is the need for high-radiated power to ensure a return signal from the target, especially necessary if a long distance of activity is desired. Another disadvantage concerns the small amount of energy returned to the receiver. It can be easily disturbed by target changes, turbine blade attitude, signal attenuation due to heavy rain, etc. This can cause the displayed target to "bleach" the images.

2.2 Secondary surveillance radar-SSR

It is interactive radar because it requires cooperation with the monitored target. SSRs are considered tracking systems, allowing the identification of allied or hostile targets. SSR sends a coded interrogation signal received by the transponder system. It decodes this signal and responds with an encoded signal with identification information. The interrogation and response frequencies are different from each other, different from the primary radar so that these signals do not interfere.

The SSRs advantage is that the signal received from the transponder is stronger than the reflected signals coming from the primary radar and not influenced by the interferences that can affect the signal received from the primary radar. The SSR system does not depend on the reflection of the signal directly transmitted as a query, because the signal emitted by the transponder is on another, different frequency. Thus, propagation errors in any direction are minimal and allow the use of smaller antennas for SSR, which are harder to detect. The disadvantage of SSR is that it can only monitor objects equipped with a functional transponder or that are not turned off, otherwise, it cannot track the target. Under these conditions, only primary surveillance radar can detect and track the target.

2.3 Weather radar-WR

This type of radar is used to monitor weather conditions. They use Doppler frequency shift, but differently than air surveillance radars. For monitoring weather conditions, snow, rain or especially hail, the Doppler frequency change is too small to measure accurately using a single pulse. Thus, weather radars use pairs of timed pulse. The difference between the phase angles of the reflections from two consecutive pulses is directly proportional to the speed of the particles, which approach or move away from the radar. By combining these measurements for several pairs of consecutive pulses, the radar is able to build a Doppler map, of the type shown on TV in the weather forecast.

3. WIND POWER FARMS

Romania has a high wind potential that attracted many foreign investors in the wind farms realization. Such an example is the construction of the wind farm at Cogealac-Fantanele, Constanta County, with a capacity of over 600 MW, [5]. It is the largest onshore wind farm in Europe. Taking into account the progress recorded regarding the dimensions and performances of the wind turbines, a newly updated map of the wind potential of Romania was realized for an altitude of 50 m, Fig. 6.

Dobrogea area with Constanta and Tulcea counties and the south and center of Moldova are favorable from the point of view of wind potential. Next, the main steps followed in the design of a wind farm near the Bacau military airport will be presented.

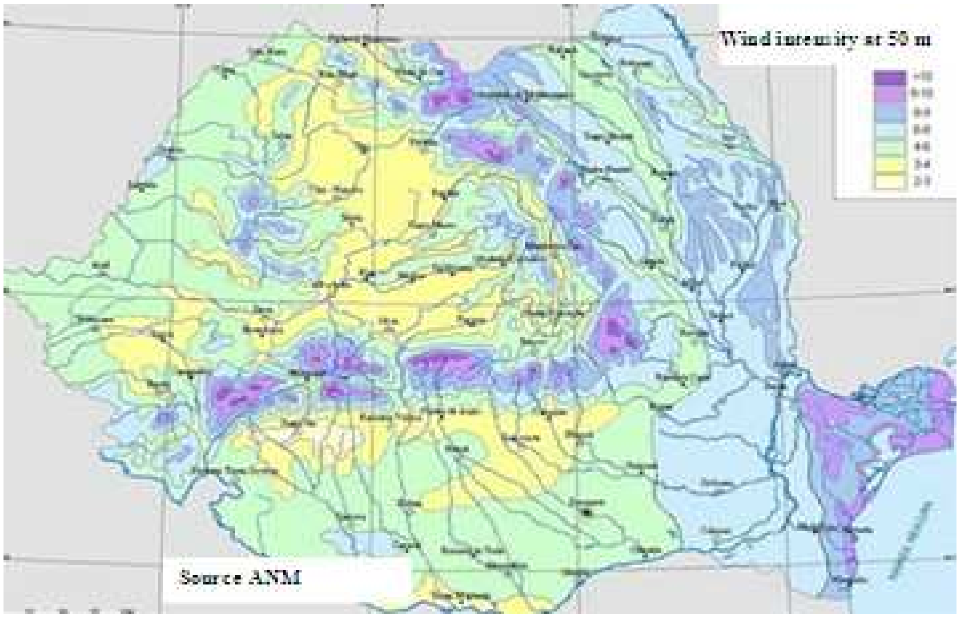

Fig.6. Wind intensity at 50 m

3.1 Measurements of air parameters, wind velocity and direction

In the respective area, two poles of 80 m height were installed to monitor environmental parameters at 10 m from the ground and wind speed and direction at 50 m, 60 m, and 70 m with three anemometers, respectively six wind vanes. Measurements were made over two years. At a height of 10 m, the solar radiation, temperature, pressure, and air humidity were measured. Fig. 7 shows images of monitoring poles with an anchoring system at every 10 m height in four directions. At the top is a red ON-OFF lighting lamp for the night and a lightning rod. At 10 m, a data logger with a solar panel records the measured data and transmits them by GSM. There is also a storing system, with a capacity of up to 30 days.

Fig.7. The monitoring mast with the anchoring system and data-logger

The data logger records every 10" (seconds) the wind intensity and direction. These values are averaged over 10' (minutes), together with standard deviation, air temperature, pressure, humidity, and solar radiation, in binary files. These are converted to ASCII files with specialized acquisition software. The values were averaged at 10' and the wind rose was made, for each anemometer from the 3 location heights. Tables 1-3 show some of the measurements recorded for the wind intensity and its turbulence.

Table 1

Selection of the wind intensity measured values.

Day	**12.2018**			**01.2019…**			**03.2021**		
level	70	60	50	70	60	50	70	60	50
1	16	12	11	12	10	6	13	9	8
2	13	9	7	18	14	12	12	8	7
3	12	8	6	17	14	11	13	9	8
..	..	..	..	..	..	..	..	..	..
30	11	10	9	16	12	11	12	8	8
31	12	11	10	15	11	10	11	7	7

Table 2

Wind turbulence intensity.

Intensity	**NNE**	**NE**	**ENE**	**..**	**NW**	**N**
…. 9	0.137	0.124	0.118		0.12	0.13
9.5	0.129	0.125	0.123		0.12	0.12
10	0.135	0.123	0.121		0.14	0.13
10.5	0.123	0.128	0.121		0.12	0.12
11	0.127	0.124	0.122		0.13	0.12
12…	0.128	0.122	0.123		0.14	0.13

Table 3

Maximum values of wind intensity.

Month	Max. Velocity 10' (m/s)		
	70 m	**60 m**	**50 m**
12.2018	18.17	17.88	16.63
…	….	….	….
04.2019	28.13	17.62	16.71
05.2019	45.8	19.39	19.13
06.2019	36.27	21.2	20.84
07.2019	36.17	19.37	18.6
08.2019	33.33	14.05	13.27
….	….	….	….
03.2021	28.42	19.11	17.6

For a correct modeling of the yield of the future wind farm, some additional calculations are made regarding the influence of the roughness of the land, the mutual influence of the wind farm turbines, etc.

3.2 Influence of soil roughness

Turbulence and wind direction are influenced by the land surface and possible existing buildings, up to altitudes of 100-150 m. Near the ground, the wind direction is slightly disturbed by the Coriolis force produced by the earth's rotation. The analyzed area in the south of Moldova and Dobrogea is characterized by a relatively flat surface with slight hills, being near the two riverbeds of the Siret tributaries, oriented slightly NW-SE, with a medium slope specific to the plain. The adjacent land was mainly used for agriculture. In the current war conditions, radars are installed near the wind power plant that monitors the eastern flank of the NATO territory. In the land vicinity, there are three domains considering the roughness influence on the wind distribution: a laminar substrate, a buffer layer, and a turbulent layer.

The logarithmic laminar law is valid for heights up to 5-20 m, the buffer layer is up to about 100 m, and above the wind velocity distribution becomes turbulent. Based on the altimetry model, the roughness of the land used in the subsequent calculations was determined, illustrated in Fig.8. The velocity profile is usually estimated by calculating the frictional stress τ that varies with altitude - z:

$$\frac{\tau}{\rho} = \left(\frac{\kappa}{\ln\left(z_2 / z_1\right)} \right)^2 \left(u_2 - u_1\right)^2 \qquad (1)$$

where: κ - von Karman constant, κ= 0.35-0.43, z_1, z_2, u_1, u_2-altitude coordinates and wind velocity at medium roughness and upper level.

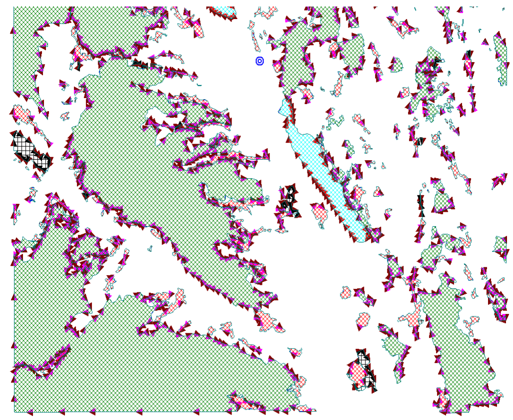

Fig.8. Roughness of the wind turbine power plant area

3.3 Wind turbines characteristics

Based on the wind turbines used in the previously built wind power plants, at this wind farm, VESTAS V100-1.8 MW and GE 2.5xl turbines were used, with the characteristics mentioned in Table 4, where D - rotor diameter, H_h - hub height, P - power capacity.

Table 3

Wind turbines characteristics.

Type	D [m]	H_h [m]	P [kW]
V100	100	105	1800
GE2.5x	100	100	2500

The turbines were selected according to some requirements of the investors:

- Generator axis at a sufficiently height from the ground to minimize the influence of constructions and the land roughness;
- Average values of wind speed at the level of the rotor axis to be in a range in accordance with the optimum operation of the turbines,
- Turbines at a competitive price.

For each turbine, the curve of power and the operating yield were determined. In Fig. 9 the obtained efficiency - C_e and reliability - C_r coefficients are illustrated. The number of turbines in the wind farm was established, associated with the necessary correction factors, considering the mutual influence and the disturbances that may occur during operation, generated by parasitic vortices behind the rotors and the wind velocity fluctuations.

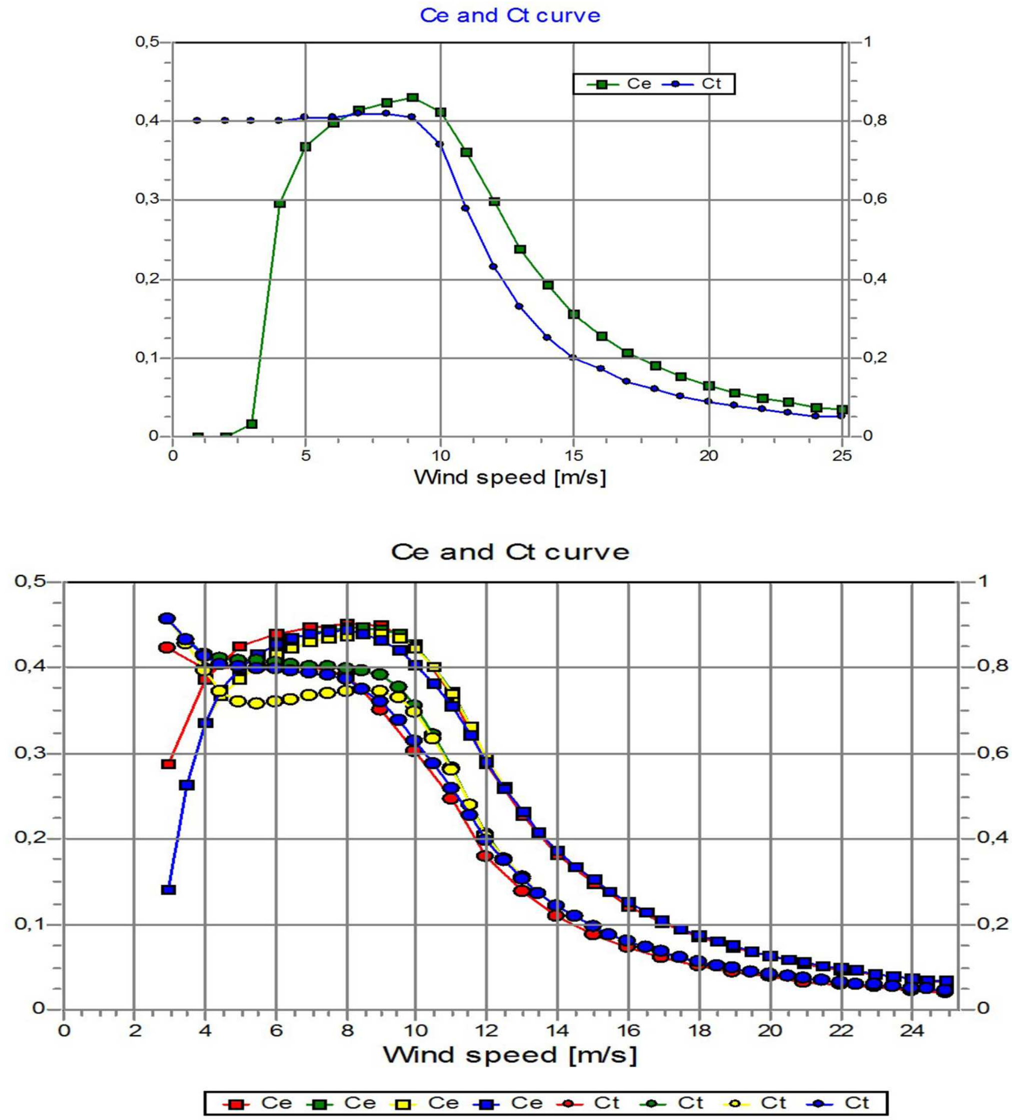

Fig.9. C_e and C_r coefficients for GE2.5x and V100

The criterion of the minimum necessary distance between wind turbines was respected to minimize the mutual influence and to ensure optimal circulation of the wind towards all the turbines. Fig. 10 shows the wind farm built in the first stage with 27 turbines, and Table 4 shows the energy values produced for each direction, with turbine GE2.5xl, in MWh.

Here the notations are: BE- Basic energy, RE-Resulting energy, *)- Energy increase due to the presence of a hill, **)-losses.

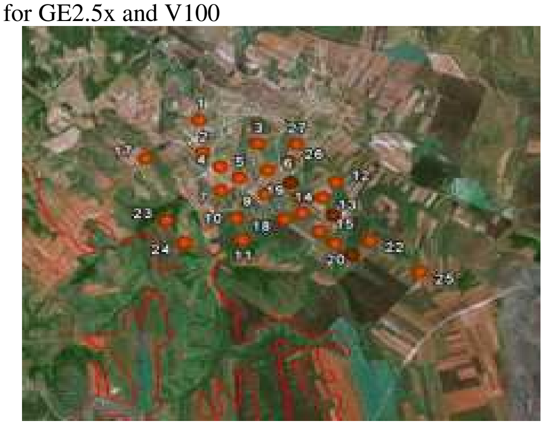

Fig.10. Wind power plant-Stage 1

Each turbine in the wind farm operates with certain efficiency, given by its relative position to the other turbines, geographical position, air currents, possible disturbances, etc. Thus, the operational efficiency of the entire wind farm and its energy production must be analyzed.

Table 4

Title of table - center aligned and justified, 10 point, bold.

Sector	N	NNE	ENE	…	Total
BE	37715	7374	5919		244861
*)	656	266	181		2866
**)	-1129	-12,1	-47,7		-6891
RE	37242	7629	6052		240837

4. INFLUENCE OF WIND TURBINES ON RADARS FUNCTIONING

If there is a natural or artificial obstacle between the radar and the wind turbines, due to the diffraction of electromagnetic waves around the obstacles, the effective height of the obstacle that can affect the operation of the radar is obtained by subtracting from the effective height of the obstacle the radius of the first Fresnel zone, $R_f = \sqrt{D\lambda}$, where: λ - length of wave, Fig.11, d_1 - distance between radar-obstacle, d_2 - distance between turbine- obstacle, and $\frac{1}{D} = \frac{1}{d_1} + \frac{1}{d_2}$, where: A-from optical point of view, B- Electromagnetic induced waves.

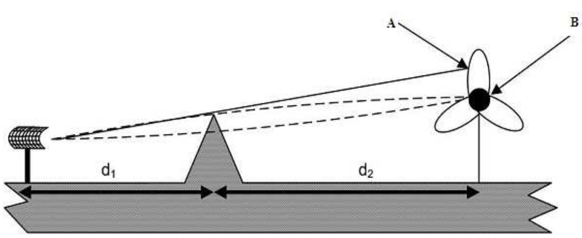

Fig.11. The shadowing area

Wind turbines currently have average heights between 80-200 m. The radar perceives them as stationary reflectors without Doppler reflections. In the nacelle is the generator. New generations of turbines allow the platform to rotate 360° to adapt to the wind direction, ensuring maximum efficiency, [6]. The rotation speed of the nacelle is relatively low, so the nacelle appears on the radar as a stationary object even when rotating slowly.

The turbine blades are big. At modern turbines, their attack angle is controlled by a computer to convert the high energy of the wind and transform it into a low speed of the turbine rotor, [7]. The new generation of turbines blades is fiberglass with metal inserts, which may include surface-mounted cables and internal lightning protection, with additional vibration-damping control systems. The platform rotates until the blades are perpendicular to the wind direction, ensuring a constant airflow. Thus the rotation speed of the rotor is about 10-20 rpm. Higher speeds are not allowed to limit the magnitude of centripetal forces and minimize noise generation, [7, 8].

The significant size of the wind turbine blades creates a target with a large reflective surface, regardless of whether it is seen by radar from the front or the side. The blades appear on the radar as a moving target with significant size. Objects located in the direction of the electromagnetic wave propagation affect its characteristics. This implies either the blocking of propagation or interference in the continuity of the wave due to diffraction caused by singular or multiple objects. The effect is called "shading" of the radar beam. The presence of even a single obstacle in the direction of electromagnetic wave propagation causes its blocking, the area behind being no longer visible to the radar. If the turbines are close to the radar, completely or partially "covered" areas appear. An estimation of false targets occurrence should include, [9]:

- Calculation of the amount of energy reflected by the wind power plant that takes into account the different orientations of the nacelle, the position of the blades, the radar frequencies, the environmental conditions, and the reflections from the nearby area;
- The impact of the electrical energy produced on the fixed target display systems considering the receiver sensitivity, time automatic adjustment of the amplification, the type of antenna, the Doppler filtering, and the minimum power at reception.

Another mechanism that can generate false targets is the reception of signals from real targets but reflected by wind turbines or reflections from the wind turbine which end up being reflected in the aircraft.

5. OBTAINED RESULTS

5.1 PSR- primary surveillance radar

There are 4 cases regarding the possibilities in which the radar, aircraft to be monitored, and the wind turbines can be positioned. They produce echoes and reflected signals received by the radio location system. For each case, the power of the reflected signal generating reflection-P_{ref} and the volume around the wind power plant where the aircraft must be to generate a reflexive wave-V, are determined.

Case 1 - The reflection occurs at the height of the wind turbine and the reflected signal is received in the main lobe:

$$P_{ref,1} = \frac{\sigma_a \cdot \sigma_{t1} \cdot \sigma_{t2} \cdot F_{rt}^2 \cdot F_{ta}^2 \cdot G_e \cdot P_e \cdot G_r \cdot \lambda^2}{(4\pi)^5 \cdot D_{rt}^4 \cdot D_{ta}^4} \quad (2)$$

$$V_1 = \sqrt[4]{\frac{\sigma_a \cdot \sigma_{t1} \cdot \sigma_{t2} \cdot F_{rt}^2 \cdot F_{ta}^2 \cdot G_e \cdot P_e \cdot G_r \cdot \lambda^2}{(4\pi)^5 \cdot D_{rt}^4 \cdot P_{\min,rec}}} \quad (3)$$

Case 2 - The reflection occurs at the wind turbine level and the reflected signal is received in all lateral lobes:

$$P_{ref,2} = \frac{\sigma_{a2} \cdot \sigma_{t1} \cdot F_{rt} \cdot F_{ta} \cdot F_{ra} \cdot G_e \cdot P_e \cdot G_{rl} \cdot \lambda^2}{(4\pi)^4 \cdot D_{rt}^2 \cdot D_{ta}^2 \cdot D_{ar}^2} \quad (4)$$

$$V_2 = \sqrt{\frac{\sigma_{a2} \cdot \sigma_{t1} \cdot F_{rt} \cdot F_{ta} \cdot F_{ar} \cdot G_e \cdot P_e \cdot G_{rl} \cdot \lambda^2}{(4\pi)^4 \cdot D_{rt}^2 \cdot D_{ar}^2 \cdot P_{\min,rec}}} \quad (5)$$

Case 3 - The reflection occurs at the wind turbine level and the reflected signal is received only in one lateral lobe:

$$P_{ref,3} = \frac{\sigma_{a1} \cdot \sigma_{t2} \cdot F_{ra} \cdot F_{ta} \cdot F_{rt} \cdot G_e \cdot P_e \cdot G_{rl} \cdot \lambda^2}{(4\pi)^4 \cdot D_{ra}^2 \cdot D_{ta}^2 \cdot D_{tr}^2} \quad (6)$$

$$D_3 = \sqrt{\frac{\sigma_{a2} \cdot \sigma_{t1} \cdot F_{ra} \cdot F_{ta} \cdot F_{tr} \cdot G_e \cdot P_e \cdot G_{rt} \cdot \lambda^2}{(4\pi)^4 \cdot D_{ra}^2 \cdot D_{tr}^2 \cdot P_{\min,rec}}} \quad (7)$$

Case 4 - The reflection occurs at the wind turbine level and the reflected signal is received only in one lateral lobe:

$$P_{ref,4} = \frac{\sigma_t \cdot \sigma_{a1} \cdot \sigma_{a2} \cdot F_{ra}^2 \cdot F_{ta}^2 \cdot G_e \cdot P_e \cdot G_r \cdot \lambda^2}{(4\pi)^5 \cdot D_{ra}^2 \cdot D_{ta}^2} \quad (8)$$

$$D_4 = \sqrt[4]{\frac{\sigma_t \cdot \sigma_{a1} \cdot \sigma_{a2} \cdot F_{ra}^2 \cdot F_{ta}^2 \cdot G_e \cdot P_e \cdot G_r \cdot \lambda^2}{(4\pi)^5 \cdot D_{ra}^4 \cdot P_{\min,rec}}} \quad (9)$$

where: $D_{rt}(m)$, $D_{ra}(m)$, $D_{ta}(m)$ -distances between radar-turbine, radar-aircraft, aircraft-turbine, λ - wavelength, G_r, G_{rl} -Gain of the reception antenna on the main and on secondary lobes, G_e-Gain of the emission antenna, $\sigma_a(m)^2$– effective reflection area of the aircraft, with $\sigma_{a1}(m^2)$–for the signal from the radar to turbine and $\sigma_{a2}(m^2)$- for the signal from the turbine to radar, $\sigma_t(m^2)$- effective reflection area of the aircraft, with $\sigma_{t1}(m^2)$–for the signal from the radar reflected to aircraft and $\sigma_{t2}(m^2)$– from the aircraft reflected to turbine, $F_{rt} = F_{tr}$ – attenuation factor induced by the field between the radar and turbine, $F_{at}=F_{ta}$ – attenuation factor between aircraft-turbine, and $F_{ra} = F_{ar}$ – attenuation factor between radar-aircraft.

5.2 SSR- secondary surveillance radar

A wind turbine located near an SSR can negatively influence its ability to detect an aircraft in the same direction as the wind turbine. The impact on SSR must be estimated separately for the interrogation and the response signal. The received power density-P_r is determined at the distance-D from the emitter, with a power signal -P_e in space:

$$P_r = \frac{F \cdot G_e \cdot P_e \cdot G_r \cdot \lambda^2}{(4\pi D)^2} \quad (10)$$

If this signal is reflected by an object, such as a wind turbine, and not directly received, Eq. (10) becomes, with P_{ref}- the received power:

$$P_{ref} = \frac{\sigma \cdot F_{et} \cdot F_{tr} \cdot G_{et} \cdot P_e \cdot G_{rt} \cdot \lambda^2}{(4\pi D)^2 \cdot D_{et}^2 \cdot D_{tr}^2} \quad (11)$$

By replacing P_{ref} with the $P_{min,rec}$-minimum reception power, the distance from turbine to the receiver for the reflected signal is:

$$D_{tr} = \frac{D_{et}}{\frac{D_{et} \cdot \lambda}{S^2}\left(1-\sqrt{A}\right)^2 - 1} \quad (12)$$

where

$$A=\left(1-\sqrt{\frac{P_{ref}}{P_{direct}}}\right)^2=\left(1-S\cdot\sqrt{\frac{D}{D_{et}\cdot D_{tr}\cdot\lambda}}\right)^2 \quad (13)$$

An attenuation of 3dB for SSR was considered acceptable.

For a wind turbine with the diameter of the generator of 6 m and height of 200 m (pillar plus rotor blade), the maximum length of the shading area was obtained as 1600 m, height 310 m, and width 45 m. The calculation was made for a single turbine. For wind farms located in the width of the main lobe of the radar antenna, the shaded area will be larger.

The case where the interrogation signal is reflected by the wind turbine was analyzed. Transponders on board aircraft have a blocking period of 35 µs after receiving an interrogation signal through the secondary lobes. Any transponder less than 5250 m away does not respond to reflected interrogation signals because the path difference between the direct and reflected signal is less than 35 µs. If the distance is greater, the minimum power of the interrogation signal reflected and received by the transponder is calculated and compared with the minimum reception power of -77 dBm.

The following values were obtained:

$P_{min,rec}=10^{-10.7}$W; $P_e = 2$ kW;
$D_{tr} = 5250$ m; $\sigma = 35$ dBm^2=$10^{3.5}$ m^2;
$G_{et} = 27$ dB; $G_{tr} = 1$;
$F_{et} = F_{tr} = 1$; $D_{et} = 15698$ m
λ=0.2913 m (for frequency 1030 Mhz)

In 2018, a TPS-79R Gap Filler radar was installed near the wind farm, and flight tests were organized to determine the influence of the reflections generated by the wind turbines on the radar performances. The aim was to determine the probability of detecting an aircraft flying behind, above, and in the vicinity of the wind farm. The distances were chosen between 5 and 15 km from the radar.

Another objective was to assess the impact on the radar caused by the reflective surfaces of the turbines combined with the Doppler frequency produced by the rotating blades, on the radar's ability to distinguish reflections from wind turbines from a possible aircraft. The radar was secondly located 12 km and 16 km from the wind farm, and the flights were carried out in two days, with aircraft at altitudes between 500-1000 m and by helicopter at altitudes between 200 - 500 m.

6. CONCLUSION

Following the flights, it was observed that the TPS-79R radar is strongly influenced by the reflections produced by the effective surface of the wind turbine rotors, combined with the Doppler frequency changes produced by the rotation of the rotors.

On the Doppler map provided by the radar, the wind farm appears as a well-pronounced relief formation that is not removed by increasing the signal processing threshold from 9 to 12.

The intensity of reflections is influenced by the turbines' speed rotation and by the number of active wind turbines in operation. On the radar screens, in the area of the wind farm, primary plots are initialized and maintained for several scanning periods/antenna passes, even tracks are initialized, with speeds varying between 150-850 km/h and heights varying between 100 - 6500 m.

For aerial targets at heights of over 500 m, above and behind the wind farm, discontinuities appear in their tracking, the signal is lost for several periods of airspace probing, mainly at the PSR.

The aerial targets that evolved at heights below 400m, above and behind the wind farm could not be tracked due to the reflections from the wind power plants.

The location of the wind power plants near the radars makes it almost impossible to detect the aircraft that evolve at low altitudes. For the PSR and SSR radars to be functional, they must be located at a distance of at least 16 km from the wind power plant.

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Influența fermelor eoliene asupra funcționării eficiente a radarelor terestre

În contextul internațional actual, când spațiul aerian trebuie monitorizat în permanență, România, granița de est a NATO, se confruntă cu noi probleme privind influența parcurilor eoliene asupra radarelor terestre. În apropierea zonei de conflict se află centrale eoliene mari, care uneori pot interfera cu radarele terestre. Distanța și direcția obiectului monitorizat sunt estimate prin evaluarea ecoului produs. Frecvența radio transmisă poate fi perturbată de un obiect reflectorizant, cum ar fi palele turbinei eoliene, în mișcare, pentru unele orientări produse de direcția vântului. Sunt prezentate câteva elemente referitoare la radarele terestre, aspecte teoretice și experimentale, asociate cu rezultatele măsurătorilor, și câteva concluzii, pentru a ilustra posibila influență a turbinelor eoliene asupra capacității de supraveghere a spațiului aerian.

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