Research and evaluation of factors affecting propagation performance in high-frequency surface wave radar (HFSWR) systems

Luu Duc Tho*, Trinh Xuan Tho, Nguyen Van Phu

Institute of Defense Equipment, Academy of Military Science and Technology, 17 Hoang Sam, Nghia Do, Hanoi, Vietnam.

*Corresponding author: luuductho1991@gmail.com

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ABSTRACT

High-frequency surface wave radar (HFSWR) systems operating in the HF band (3–30 MHz) enable the detection of targets beyond the horizon by exploiting the electromagnetic surface wave. However, the propagation characteristics of HF waves are strongly affected by environmental conditions such as ionospheric electron density, geomagnetic disturbances, temperature, humidity, atmospheric noise, and terrain and geographical features. This paper presents combined research and simulation results to evaluate the extent to which these factors influence HF wave propagation under surface wave radar operating conditions. The results show that variations in environmental conditions lead to fluctuations in propagation loss, which directly affect the detection probability and the effective operating range of the radar system. The paper presents calculation and simulation results at a frequency of 10 MHz. The research results can provide a scientific basis for proposing design, fabrication, and deployment solutions for surface wave radar systems that are suitable for the natural conditions in Vietnam.

Keywords: Surface wave radar; HF waves; Radar cross section; Ionosphere; Electromagnetic wave propagation.

1. INTRODUCTION

High-frequency surface wave radar (HFSWR) exploits the ground-wave propagation of HF electromagnetic waves, which travel along and follow the Earth’s surface due to interaction with conductive media such as seawater. By radiating at very low elevation angles, the surface wave can propagate beyond the geometric horizon with relatively low attenuation, enabling long-range maritime surveillance. Consequently, the performance of HFSWR strongly depends on the electrical conductivity of the propagation medium, such as seawater, freshwater, and land surfaces. This propagation mechanism is fundamentally different from ionospheric reflection (sky-wave propagation), where HF signals are refracted or reflected by the ionosphere and return to the Earth after atmospheric propagation. While ionospheric reflection is strongly affected by solar activity and diurnal variations, surface wave propagation is comparatively stable and predictable. Therefore, SWR systems primarily rely on surface-wave propagation rather than ionospheric reflection.

Currently, long-range maritime surveillance radars have attracted significant attention and investment from developed countries, and numerous related studies have been published in reputable international journals. However, these studies are generally applicable only to specific geographical regions where such systems have been developed. Meanwhile, in Vietnam, there have been no in-depth scientific publications in this field to date. References [1-7] present studies on the effects of weather conditions and the marine environment on HF wave propagation, while references [8–10] investigate the impact of wind turbines on HFSWR systems. In [13-14], several studies have presented evaluations of target detection performance as well as interference suppression and clutter mitigation techniques for HFSWR systems. These works indicate that optimizing the overall performance of HFSWR remains a challenging problem for researchers and practitioners. Therefore, research aimed at mastering the assessment of factors affecting HF wave propagation under various conditions is of critical importance. This research serves as a foundation and a prerequisite for establishing system architectures in the design, fabrication, and deployment of surface wave radar systems in Vietnam.

2. PROBLEMS, RESULTS AND DISCUSSION

2.1. Overview of surface wave radar

Surface wave radar (HFSWR) employs a vertically polarized antenna array installed close to the seashore in order to take advantage of the surface wave propagation effect of HF-band radio waves. When vertically polarized electromagnetic waves interact with the sea surface, a phenomenon known as the "surface wave effect" occurs, enabling the waves to propagate along the sea surface over distances beyond the radio horizon. The propagation capability is significantly affected and strongly attenuated when waves travel over land or freshwater surfaces. HFSWR systems are capable of observing and detecting maritime targets on the sea surface at ranges of up to 400 km [11]. Figure 1 presents an overview of an HFSWR system.

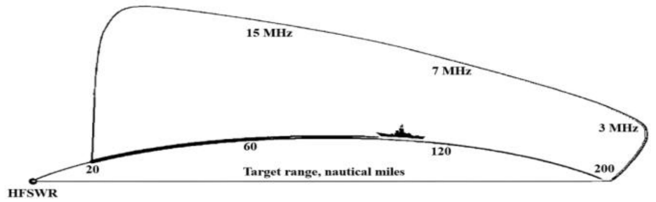


Figure 1. *Comparison of detection range of HFSWR.*

For HFSWR systems, there are numerous factors that affect target detection capability, such as weather conditions, geographical and terrain effects, and marine environmental factors.

2.2. Assessment of the impact of weather factors

Under the weather conditions in Viet Nam, characterized by high temperature, high humidity, and significant rainfall, radio wave propagation may experience certain environmental influences. However, because HF radar operates at much lower frequencies than those significantly affected by meteorological phenomena (typically above 11 GHz), the direct impact of rainfall on HF wave propagation is negligible. In most cases, even heavy rainfall introduces only minor time-varying fluctuations in the propagation channel rather than significant attenuation, and thus does not fundamentally degrade the characteristics or overall reliability of HF signals.

In addition to the well-known edge clutter and the influence of Bragg lines, which depend on wind conditions, the Pierson–Moskowitz (PM) fully developed sea-state wave energy spectrum model describes the wave energy spectral density as a function of angular frequency ω (*rad/s*):

$$S_{PM}\left(\omega\right)=\alpha g^2\omega^{-5}\exp\left(\frac{-5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right) \quad (1)$$

Where: $g=9.81m/s^2$ - is the gravitational acceleration; α=0.0081 – is an Empirical constant; $\omega_p=0.26\pi g/U_{10}$ - is the angular frequency at the spectral peak (*rad/s*); U_{10} - is the wind speed at a height of 10 *m* (*m/s*).

Therefore, wind speed affects the sea-wave energy spectrum under fully developed sea-state conditions. As a specific example, Figure 2 illustrates the relative noise power in the frequency band from 5 to 25 MHz as influenced by wind at Beaufort scale levels 4 (6.0 m/s), 6 (12 m/s), and 10 (25 m/s). In the selected model, $\gamma=3.3$ corresponds to a typical JONSWAP spectrum, and $n=3$ the noise-to-radar-signal ratio, or simply that the noise decays more rapidly than the radar signal.

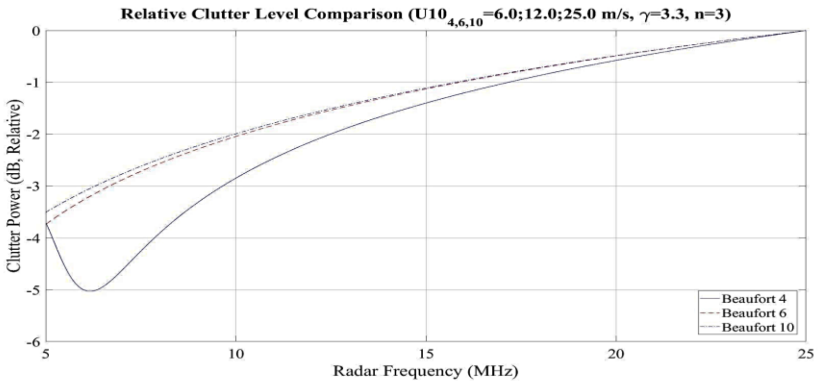


Figure 2. *Effect of wind on HF waves.*

From the calculation results shown in Figure 2, it can be seen that the higher the frequency, the stronger the wind-induced noise, which implies an increase in overall noise levels.

2.3. Assessment of the impact of terrain and geographical factors

The locations where HFSWR systems are deployed pose several geographical and terrain-related challenges. For example, complex coastlines inherently create difficulties for accurate mapping. The "coastline paradox" illustrates that a coastline does not have a well-defined length due to its fractal nature, meaning that the measured length depends on the measurement method and the level of map generalization. This inherent irregularity can affect the accuracy of HFSWR mapping, as the spatial resolution of the radar interacts with small-scale features of the coastline.

In addition, ground characteristics vary along the propagation path, leading to surprisingly large variations in the received field strength with distance. For a propagation path extending over land, then sea, and then land again, the field strength gradually decreases over the initial land region; upon reaching the coastline, it recovers with a rapid increase, then decreases gradually, and finally drops sharply when crossing the coastline once more. Early methods for addressing this problem produced inaccurate results and failed to satisfy reciprocity requirements. Millington established a procedure that enforces reciprocity and proved to be highly satisfactory for relatively smooth terrain, yielding good results.

Figure 3 illustrates Millington's procedure for a land–sea–land propagation path, represented by the ground-wave field strength curve for the initial land section.

This procedure is described as follows: for a given frequency, the curve corresponding to section S_1 is selected, and the field strength $E_1(L_1)$ at distance L_1 is recorded. The curve for section S_2 is then used to determine the fields $E_2(L_1)$ and $E_2(L_1+L_2)$. Similarly, using the curve for section S_3, the fields $E_3(L_1+L_2)$ and $E_3(L_1+L_2+L_3)$ are obtained, and this process continues in the same manner.

The received field strength is then determined by:

$$E_R = E_1(L_1) - E_2(L_1) + E_2(L_1+L_2) - E_3(L_1+L_2) + E_3(L_1+L_2+L_3) \tag{2}$$

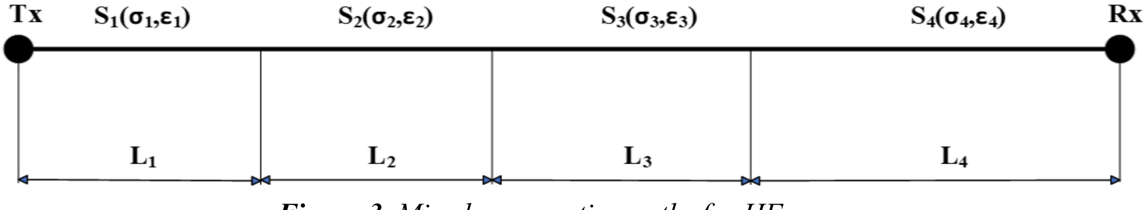


Figure 3. *Mixed propagation paths for HF waves.*

The procedure is then reversed, with R considered as the transmitter and T as the receiver, yielding the field E_T, which is expressed as:

$$E_T = E_3(L_3) - E_2(L_3) + E_2(L_3 + L_2) - E_1(L_3 + L_2) + E_1(L_3 + L_2 + L_1) \quad (3)$$

Combining the above, the result is given by the following equation:

$$E_M(R) = \frac{(E_R + E_T)}{2}, (dB(\mu V/m)) \quad (4)$$

Figure 4 shows the simulated field-strength profile based on the Millington method for a mixed propagation path of 0.1 km of sand – 10 km of sea – 5 km of land – 50 km of sea at 10 MHz. The electrical conductivity parameters employed in Table 1 are adopted for the analysis.

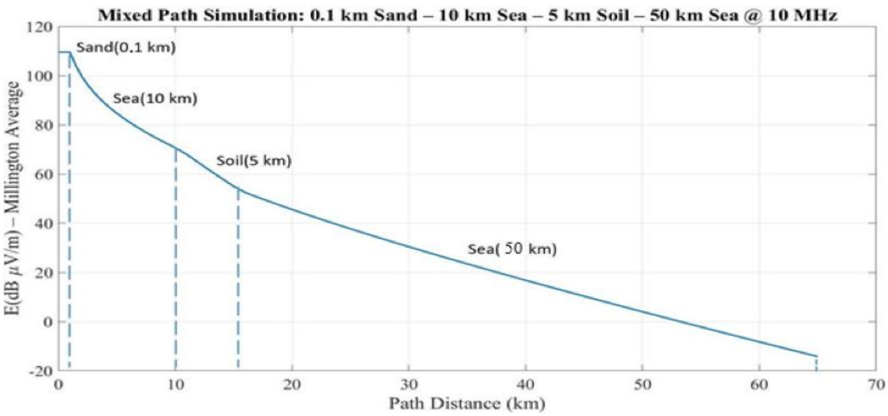


Figure 4. *Simulation of the field-strength profile using the Millington method.*

The results in Figure 4 clearly demonstrate the non-uniformity of the propagation environment. When the signal propagates over a highly conductive medium (sea), the field strength decays slowly, whereas over a poorly conductive medium (sand/land), the field strength decays more rapidly. The Millington method "smooths" the transition by averaging the forward and reverse paths (from transmitter and from receiver), so the resulting curve does not exhibit abrupt discontinuities but instead changes gradually.

2.4. Assessment of the impact of marine environmental factors

Saline seawater has higher electrical conductivity, which enables surface waves to propagate over longer distances. Salinity and water conductivity are key factors determining the propagation efficiency of HF-band signals. HF waves propagate significantly less effectively over freshwater than over seawater. This disparity arises because freshwater has an electrical conductivity approximately 333÷1666 times lower than that of seawater. The higher conductivity of typical open-ocean seawater (with salinity usually exceeding 30%) facilitates stronger coupling of HF waves with the sea surface, allowing signals to travel much farther. In contrast, periods of large freshwater discharge that reduce salinity in coastal regions have been shown to significantly degrade the effective operational range of HFSWR systems. The difference in propagation behavior over freshwater compared to seawater is substantial. Table 1 presents the electrical conductivity parameters of several common environments, as reported in [4].

The electrical conductivity of seawater is given by:

$$\sigma = 0.18C^{0.93}\left(1 + 0.02(T - 20)\right), S/m$$

Where, C – is the salinity (grams of salt per liter); T – is the temperature (°C).

Figure 5 shows the relative received power as a function of frequency and the conductivity of the propagation medium. Figure 6 shows the relative received power over the coastal waters of

Quy Nhon, Viet Nam, within a radius of 50 km, based on the reported seawater salinity data in reference [12].

Table 1. *Electrical conductivity of several typical media.*

№	Description	Electrical conductivity (S/m)	Relative permittivity
1	Seawater, low salinity	1	80
2	Seawater, average salinity	5	70
3	Freshwater	0.003	80
4	Land, average salinity	0.03	40
5	Wet ground	0.01	30
6	Land, low salinity	0.003	22
7	Medium dry ground	0.003	15
8	Dry ground	0.0003	7
9	Very dry ground	0.0001	3
10	Ice (fresh water ice), -1^{0}C	0.00003	3
11	Ice (fresh water ice), -10^{0}C	0.00001	3

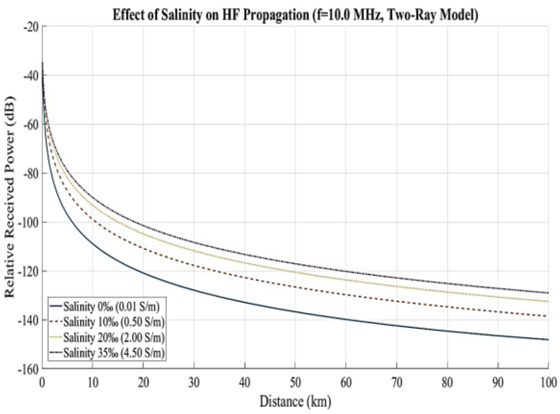


Figure 5. *Effect of salinity on HF wave propagation.*

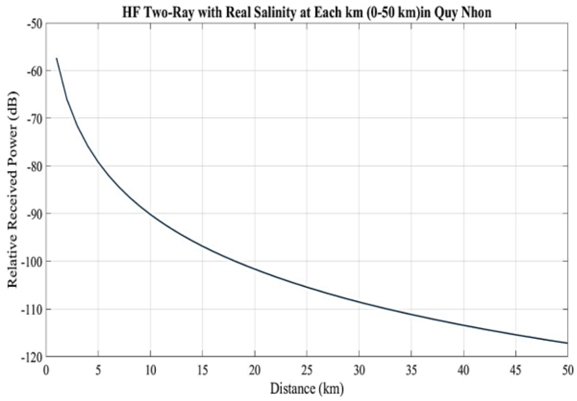


Figure 6. *Effect of salinity on HF wave propagation in the coastal waters of Quy Nhon.*

From the results shown in Figures 5–6, it can be seen that the marine environment has a significant impact on the actual received power of HFSWR stations.

2.5. Assessment of the impact of wind turbines

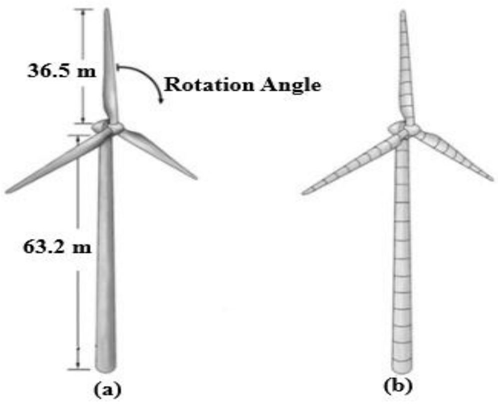


Figure 7. *Image of a 2 MW wind turbine installation.*

Among the factors affecting the propagation performance of surface wave radar, the impact of wind turbines cannot be overlooked. Figure 7a illustrates a 2 MW wind turbine model and its coordinate system. Each facet is considered to be an ideal electric conductor. If necessary in the model, composite and hybrid materials can be approximated by adjusting the reflection coefficients of individual facets. The radar cross section (RCS) of the n-th segment, σ_n, is modeled by calculating and summing the scattered signals from each facet of that segment, as illustrated in Figure 7b, using physical optics formulations. In related studies, a combination of physical optics and geometrical optics techniques has been employed to address the multiple-interaction problem among the facets of wind turbines. To compute the total RCS of the turbine components (blades, tower, or nacelle), σ_{TOTAL}, the contributions from each component can be summed according to equation (5). After determining the turbine orientation and the radar location, the distance to each segment d_n is obtained from the geometry of the scenario. This distance is then used to calculate the phase contribution of each segment. The overall RCS of a wind turbine component is determined as follows:

$$\sigma_{TOTAL} = \left| \sum_{n=1}^{N} \sqrt{\sigma_n} \exp\left(j \frac{2\pi d_n}{\lambda} \right) \right|^2 \quad (5)$$

It consists of Nsegments and is computed by applying the relative phase technique. For electrically large objects, whose RCS is dominated by surface reflections, the relative phase technique allows for a more accurate estimation of the absolute RCS. However, this technique neglects second-order effects, such as coupling at the joints between different components of the wind turbine.

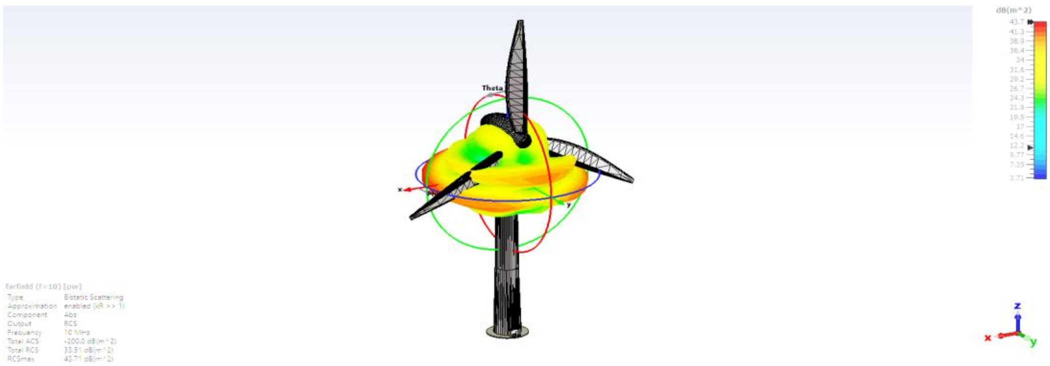
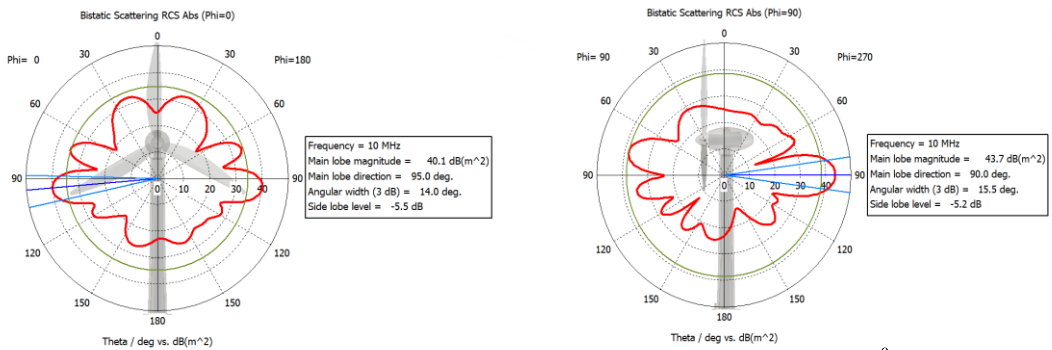


Figure 8. *3D image of the RCS distribution at an illumination angle of $\theta_0=90^0$, $\varphi_0=90^0$.*



a) $\varphi=0^0$ b) $\varphi=90^0$

Figure 9. *Calculated RCS results at an angle of $\theta_0=90^0$, $\varphi_0=90^0$.*

Wind turbines are electrically large objects in power systems; therefore, exact analytical methods often encounter significant limitations. CST is a powerful electromagnetic simulation software that is widely used for RCS analysis. Accordingly, the authors constructed detailed models and performed simulations to evaluate the RCS of wind turbines under different illumination angles in the far-field region $(2\pi d_n/\lambda) \gg 1$, as illustrated in Figures 8–11.

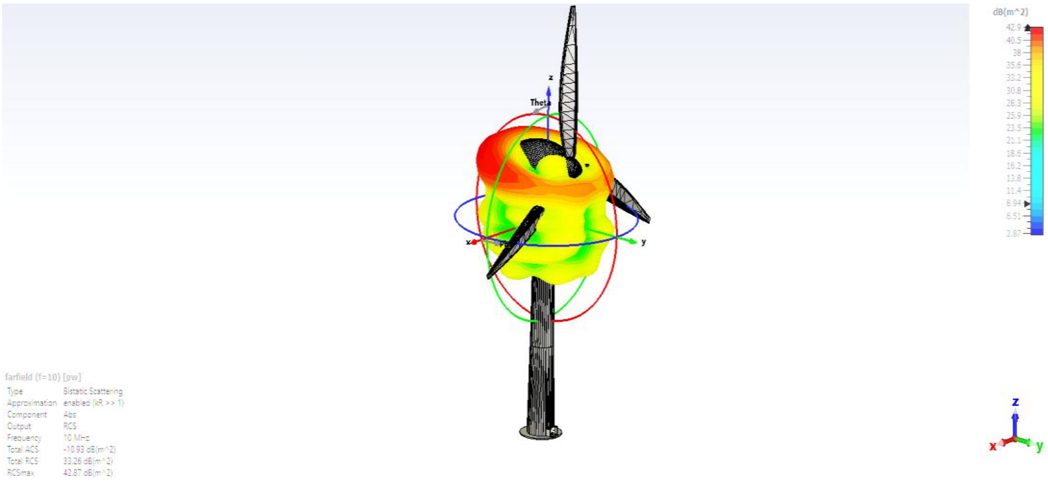
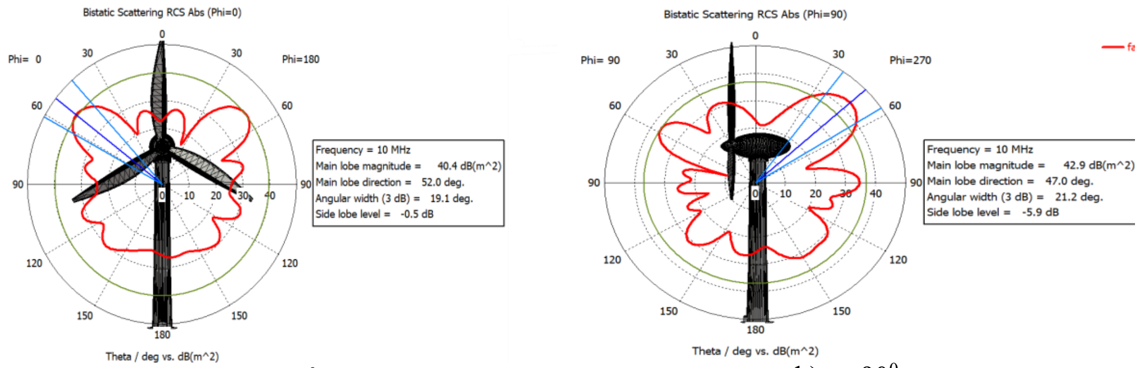


Figure 10. *3D image of the RCS distribution at an illumination angle of $\theta_0=135^0$, $\varphi_0=90^0$.*



a) $\varphi=0^0$ b) $\varphi=90^0$

Figure 11. *Calculated RCS results at an angle of $\theta_0=135^0$, $\varphi_0=90^0$.*

Through the calculation and analysis of the radar cross section (RCS) of wind turbines, the turbines are modeled as perfectly conducting structures, in which the tower and the blades are considered the primary scattering sources, while the influence of the nacelle is evaluated under representative illumination conditions. From the results shown in Figures 8–11, it can be observed that the RCS of wind turbines in the HF band is relatively significant and strongly depends on the illumination angle, wave polarization, and the rotational state of the blades (in this paper, only the stationary blade case is considered). In certain observation directions, the RCS reaches large values, which can generate background clutter, create false targets, or obscure real targets, thereby degrading the detection and tracking performance of HF radar systems. To mitigate clutter interference in HFSWR systems, clutter-generating objects should be strategically placed outside the antenna mainlobe, with sufficient radial separation from the radar site and azimuthal offset from the primary observation direction. Priority should be given to backlobe regions or naturally shielded areas to reduce received clutter power and avoid spectral overlap with the Bragg Doppler region.

3. CONCLUSIONS

This paper presents a comprehensive assessment of the factors affecting the performance of

HFSWR systems, including weather conditions, terrain and geographical features, the marine environment, and the presence of wind turbines, within the context that HF wave propagation is highly dependent on the propagation medium. Through modeling and simulation, the obtained results clearly reflect the complexity and high variability of HFSWR radar signals under real-world conditions. The findings of this study provide an important scientific basis for the design, deployment, and operation of HFSWR systems, enabling the full potential of these modern radar systems to be effectively realized.

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TÓM TẮT

Nghiên cứu, đánh giá các yếu tố ảnh hưởng tới hiệu năng truyền sóng trong ra đa sóng bề mặt (HFSWR)

Các hệ thống ra đa sóng bề mặt (HFSWR) với dải tần số HF (3–30 MHz) cho phép phát hiện mục tiêu vượt đường chân trời nhờ nguyên lý lan truyền sóng bề mặt. Tuy nhiên, đặc tính lan truyền của sóng HF chịu ảnh hưởng mạnh của điều kiện môi trường như mật độ điện tử tầng điện ly, nhiễu từ trường Trái Đất, nhiệt độ, độ ẩm, nhiễu khí quyển và địa hình, địa lý. Bài báo này trình bày kết quả nghiên cứu kết hợp mô phỏng để đánh giá mức độ ảnh hưởng của các yếu tố đến sự lan truyền sóng HF trong điều kiện hoạt động của ra đa sóng bề mặt. Kết quả cho thấy sự thay đổi các điều kiện môi trường dẫn đến sự biến thiên mức suy hao truyền sóng, ảnh hưởng trực tiếp đến xác suất phát hiện và tầm làm việc hiệu quả của hệ thống ra đa. Trong bài báo, trình bày các kết quả tính toán và mô phỏng tại tần số 10 MHz. Kết quả nghiên cứu có thể cung cấp các cơ sở khoa học để có các phương án thiết kế, chế tạo và triển khai các đài ra đa sóng bề mặt phù hợp với điều kiện tự nhiên tại Việt Nam.

Từ khóa: Ra đa sóng bề mặt; Sóng HF; Diện tích phản xạ hiệu dụng; Tầng điện ly; Lan truyền sóng điện từ trường.