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A SOLUTION FOR THE OVER-THE-HORIZON-RADAR SIMULATOR

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Abstract:

Introduction/purpose: The OTHR simulator presented in this paper is developed and used in practice, with the aim of emulating radar signal environment, but also optimizing the radar parameters in real applications such as: radiated power, antenna array gain, path loss, radar cross section, external interference, and noises.

Methods: In this paper, the methodology of mathematical modeling is used as well as simulations .

Results: Based on the performed analysis, the output data from the OTHR simulator is presented and discussed.

Conclusion: The usage of the presented OTHR simulator makes assessing the reliability of a potential radar at predetermined locations automated, controllable and efficient, with results closely matching radar behavior in real operation.

Key words: over-the-horizon-radar, radar cross-section, exclusive economic zone, radar simulator.

Introduction

The Over The Horizon Radar (OTHR) simulator presented in this paper is developed and designed in order to predict and analyze all external parameters that affect the OTHR functionality. The OTHR uses a surface wave component in order to achieve a huge coverage area. Detection and tracking of vessels with a maximal range up to 200 NM makes it suitable for application within a system for monitoring the Exclusive Economic Zone (EEZ). The EEZ is a sea belt of a certain width extending from the territorial waters in direction of the open seas, over which a coastal state has exclusive rights regarding the exploitation of biological and mineral resources of the sea (United Nations, 2011). To the best of our knowledge, there are only two ways to achieve complete EEZ monitoring. The first approach utilizes low range sensors, such as Electro – Optical (EO) camera systems and Micro-Wave (MW) radars, on the mobile platforms such as vessels and airplanes, thus avoiding sensor's limitations. The second approach uses a network of OTHR radars to ensure constant surveillance of a complete coastline well beyond the horizon. Since the price of the OTHR radar network is significantly lower than a combined cost of the aforementioned sensors and their platforms, it is clear why these radars became a sensor of choice for maritime surveillance (Sevgi & Ponsford, 1999), (Tošić et al, 2016).

The OTHR radar uses the frequency bandwidth from 3 to 30 MHz (HF) and utilizes vertically-polarized, surface electromagnetic waves which propagate above the sea or ocean surface. The usage of the surface wave OTHR is accompanied with specific issues, such as: influence of the sea state on electromagnetic wave propagation above the sea surface, impact of Earth's surface curvature on the characteristics of transmitting and receiving antenna stations, interference of other transmitting devices, atmospheric noise, space noise and man-made noise in the vicinity of OTHRs, along with the radar cross section (RCS) of targets that need to be detected and tracked (Skolnik, 1990), (Nikolić et al, 2016a), (Fabrizio, 2013), (Nikolic et al, 2018). All these issues should be taken into account properly when OTHR systems are planned for implementation. It is of great importance to analyze their effects at the early stage and calculate a corresponding system performance under the conditions of a specific deployment location. For that purpose, a computer - based simulator of the OTHR would be very practical in engineering tasks. One solution of this simulator, developed in the Vlatacom Institute and used in our projects worldwide is presented in this paper.

The simulator allows the analysis of the environmental impact on the operation of OTHR radars, as defined by the user. It should keep track of all possible changes in radar conditions in the HF frequency band, and also allow different scenarios to be set. Thus, a proper flexibility in defining simulation parameters and specific scenarios for simulation should be provided. The simulator takes into consideration the change of the RCS to determine the signal to noise ratio (SNR) for each vessel defined by the scenario, which results in data comparable with real situations, as might be acquired by the radar in practical operation. The output data from the simulator should be provided in the format of the real OTHR radar sensor, in order to validate the data by comparing it with the real OTHR system, after installation. The OTHR Simulator solution described in this paper is commonly compared with vHF-OTHR radars (Vlatacom Institute, 2018), as being completely compatible with its model and data formats.

OTHR simulator concept

The main goal of the simulator is to estimate relevant capabilities of the detection of different sizes of vessels, which is the main benchmark for this kind of radar applications (Nikolic et al, 2016b). All estimations are made by taking into account the characteristics of the environment for potential locations, since many of parameters of interest in simulation are highly dependable on particular geo-location and surroundings.

The Simulator software has been developed in the Matlab and runs on Windows OS (Girault et al, 2017). The input parameters of the Simulator are given through the simulating scenario that includes: predicted paths of vessels, speed and size of vessels, season of the year, time of the day or night, sea conditions, wind directions, and geographical coordinates of potential sites. This scenario is represented in the form of an XML file. The output of the simulator represents detected targets in the table form, defined by the vHF-OTHR interface.

The simulator is designed for the following main tasks:

- Testing the software for the detection and tracking of vessels,
- Analyzing and estimating parameters of th OTHR radar, and
- Analysis and evaluation of location-specific conditions for OTHR deployment.

The main components of the Simulator, shown in Figure 1, are:

- Step Machine: a library for creating, reading and sorting input XML files for simulation,
- Radar Model: a library for calculating the signal to noise ratio of each simulated target,
- Detection engine: a library for the detection and tracking of simulated targets.

The block named "Step Machine" is used for designing a particular simulation scenario. It includes defining: the initial coordinates of vessels and their course and speed; the basic radar parameters (the latitude and longitude of the location, the output power); the environmental parameters (the time of the year - month, the time of the day, the state of the sea and the direction of the wind). The course of a ship can be set as straightforward, curvilinear or in accordance with the given scenario. These parameters are all given in the XML format.

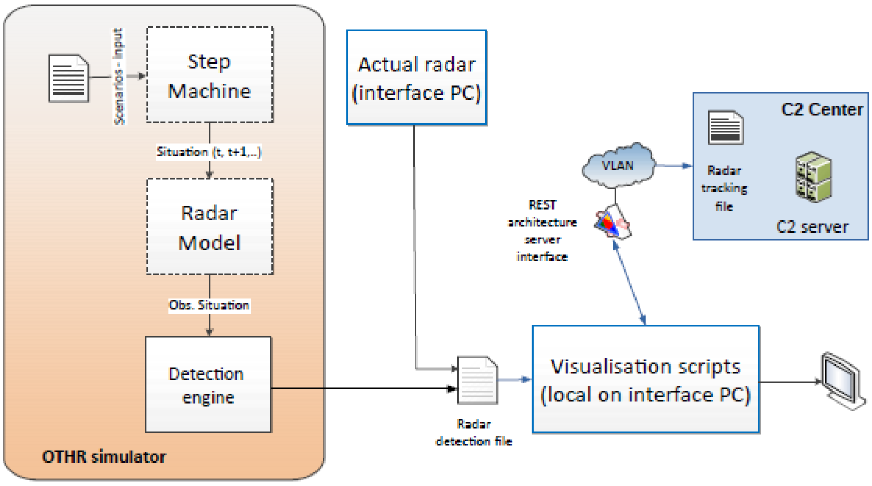


Figure 1 – Block diagram of the OTHR simulator
Рис. 1 – Блок-схема „OTHR“ симулятора
Слика 1 – Блок-шема „OTHR” симулатора

The block named “Radar Model” represents a function created in Matlab for calculating the maximum range, angular position relative to the true North and the signal to noise ratio (SNR) of potential targets. For all input data sets created by the step machine, the “Radar Model” creates a corresponding XML file with information about all potential radar targets.

This information represents an input for the last block - Detection and tracking engine.

The block named “Detection engine” imports the abovementioned information and creates a table of potential detections. In this way, the base of data sets is created in order to perform the testing of the radar tracking processes.

Usually, after the installation of the radar in practice (Actual radar block in Figure 1), the data obtained from the Simulator is compared with the data obtained from the real OTHR. All detection data obtained from installed, operational OTHR radars is sent to the Command and Control (C2) servers, via the communication network, Figure 1. The collected detection data passes through the top layer in the signal processing hierarchy – the tracking application (Stojković et al, 2016). This process of mutual comparison between simulated and real data is done and presented within Visualization scripts (Džolić et al, 2019b). In this way, additional calibration of the real OTHR radar can be performed if the results obtained in the field are different from those expected and an additional tuning of the radar system parameters is needed.

While the detection and tracking concept used in our research is already explained in detail, along with communication and data management for OTHR systems (Petrovic et al, 2020), in this paper we focus on describing the modeling process itself, which is the core of the Simulator and a true basis for all other features resulting from it. The solutions adopted in our radar model are of general importance: since they are not system-specific, they can be used within the performance analysis or simulation of any surface-wave over-the-horizon radar, of any vendor, in the manner completely independent from other blocks presented in Figure 1.

Radar model

The “Radar Model” is the most important block of the Simulator - it calculates the SNR for each target defined by a simulating scenario, shown in Figure 2.

The radar model used in the Simulator is based on the well-known radar equation, given by equation (1). This formula, unlike the classical radar equation, takes into account adaptation to the environment, frequency and waveform selection, RCS, external noises, interference, antenna gain, spatial resolution, and clutter (Skolnik, 1990).

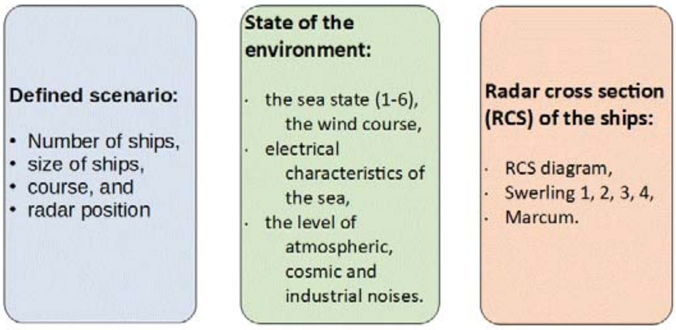


Figure 2 – Input scenario for the Radar Model function
Рис. 2 – Входной сценарий для функции модели радара
Слика 2 – Улазни сценарио за функцију радарског модела

$$S/N = \frac{P_{av} G_t G_r T \lambda^2 \sigma_{RCS} F_p}{N_0 L (4\pi)^3 R^4} \tag{1}$$

where:

- S/N stands for the signal to noise ratio,
- P_{av} stands for the average transmit power (W),
- G_t stands for the transmitted antenna gain,
- G_r stands for the received antenna gain,
- T stands for the effective processing time (s),
- λ stands for wavelength (m),
- σ_{RCS} stands for the radar cross section of a target (m^2),
- F_p stands for the propagation-path factor,
- N_o stands for the total noise power (W),
- L stands for transmission-path and system losses, and
- R stands for the distance between radar and target (m).

In practice, the S/N ratio is usually denoted in dB. The parameters from equation (1): σ_{RCS}, L, F_p and N_o are obtained from the radar model itself, as will be described later in the text. All other parameters are imported by the user.

In the considered radar model, the influence of external factors is calculated on the basis of the following sub-models:

- Sub-model 1: Sea surface propagation losses,
- Sub-model 2: Sea surface roughness impact,
- Sub-model 3: External noise, and
- Sub-model 4: Radar cross-section of vessels.

The sub-models listed above are fundamental for the simulation of the OTHR performance. While some system – specific parameters (like radiated power, antenna parameters, etc.) may vary from one particular radar unit to another, all the parameters generated through the listed sub-models are location – specific, fixed for predefined surrounding and environmental conditions, as described in detail in the rest of this section.

Sub-model1: Sea surface propagation losses

Since the OTHR radar operates in the HF band, frequencies between 4.6 and 7 MHz yield to the best range / cost performance. Moreover, with an increase in operating frequency values, signal propagation losses arise as well. The electrical characteristic of the propagation surface is mainly determined by the salinity level (ITU, 1992). Salty water when compared to dry land shows better conductivity characteristics, i.e. smaller propagation losses. This implies that OTHR radars can only operate at coastal areas (with installations close to the line of the waterfront), and are capable of monitoring large bodies of water.

For sea (salty) water, at 20 °C a value of 5 S/m is used as a world-wide average. Some areas of the Baltic Sea have a value of 1 S/m, while in the Red Sea the conductivity may exceed 6 S/m (ITU, 1992). The conductivity will however vary with both sea water salinity and temperature and it is given by:

$$\sigma_{SEA} = 0{,}18C^{0{,}93}\left[1 + 0{,}02(T - 20)\right]\frac{S}{m} \qquad (2)$$

where:

- C stands for salinity (grams of salt per liter),
- T stands for temperature (°C).

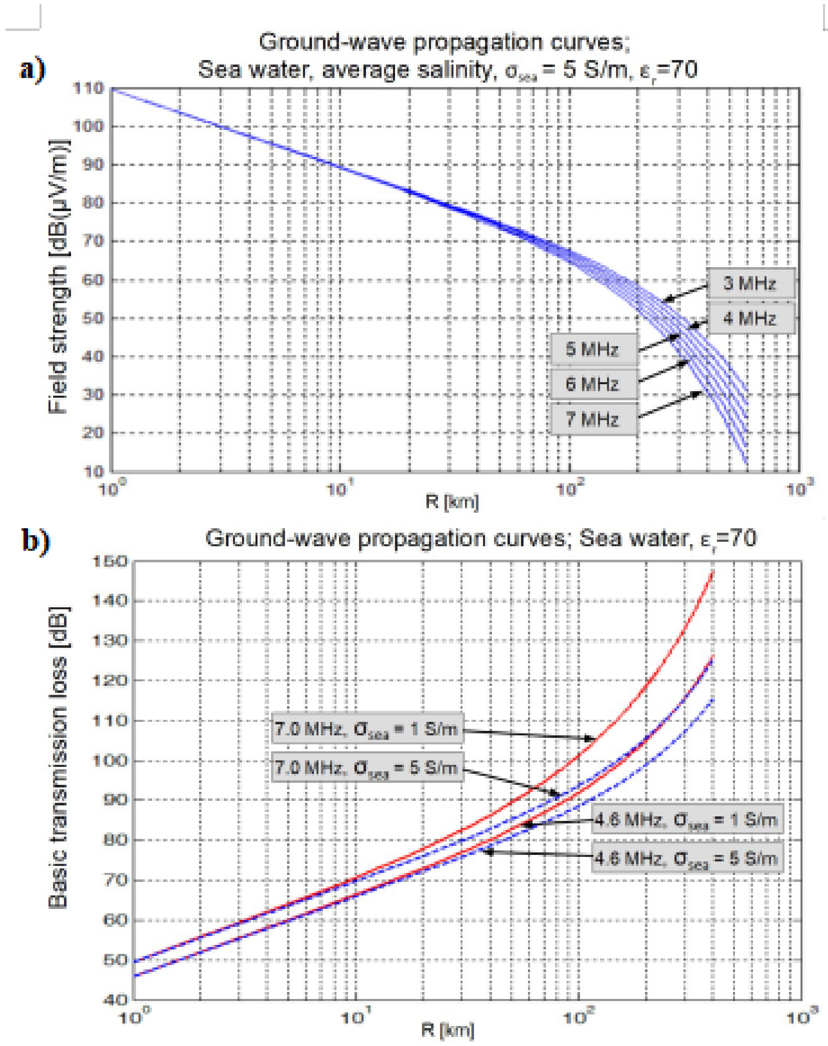


Figure 3 – Model of the signal propagation above the sea surface based on the GRWAVE software, a) Field strength, b) Transmission losses
Рис. 3 – Модель распространения сигнала над поверхностью моря на основе программного обеспечения „GRWAVE“, а) сила поля, б) потери при передаче
Слика 3 – Модел пропагације сигнала изнад морске површине заснован на софтверу „GRWAVE”, а) ниво поља, б) губици у пропагацији сигнала

The GRWAVE program (ITU, 2020) with linear interpolation between distance points is used to calculate propagation losses above the sea surface. This program uses a model that takes into account the curvature of the Earth's surface, as well as the electrical characteristics of the sea surface and non-homogenous air causing refractions. The GRWAVE runs in the DOS environment, and the results are given in the form of an TXT file. The propagation curves for the frequencies from 3MHz to 8MHz are shown in Figure 3, on the basis of the values from the TXT file generated by the GRWAVE program, for the sea water propagation with the average salinity, the conductivity of 5 S/m and the relative permeability, $\varepsilon_{r,}$ of 70.The subfigure a) in Figure 3 shows the field strength of the electromagnetic (EM) wave at particular distances. This value was taken into account to calculate the basic transmission, L, from equation (1), (ITU, 2007). The subfigure b) in Figure 3 shows a variation of L in relation to the working frequency and the sea conductivity. The only input parameter for this function is a range (i.e. distance) of interest for loss calculation.

The values obtained from the GRWAVE are incorporated further in the Matlab code of the OTHR Simulator, and used for modeling the losses in propagation corresponding to this particular Sub-model.

Sub-model 2: Sea surface roughness impact

Apart from losses described within the *Sub-model 1,* additional losses in the propagation of HF surface waves are caused by wave ripples at the propagation surface. In other words, propagation losses are also dependent on roughness of the sea surface. Roughness of the sea surface, also known as the sea state, is most commonly described with the Douglas scale. By this scale, a sea state is expressed with digits from 0 to 9. A higher number on the scale corresponds to a higher wave height, which leads to higher losses in propagation. The analysis of the sea states from 0 to 6 shows that an increase in the wave height is proportional to an increase in propagation loss. A detailed analysis of this phenomenon could be found in (Barrick, 1970).

Another Matlab function is used to describe a propagation model which addresses the impact of the sea surface roughness. The maximum radar range, sea conditions and wind directions are defined as input parameters for this Matlab function, which generates an TXT file at the output. The values from the TXT file are used for the Calculation of the parameter “L” from the radar equation (1). Figure 4 shows the signal propagation losses for the sea states 3, 4, 5, and 6 when the wind direction is in the direction of the ship (red lines), as well as when the wind direction is normal to the course of the ship (blue lines). The calculations are made based on the values taken from empirical curves (Barrick, 1970) for the 7 MHz working frequency.

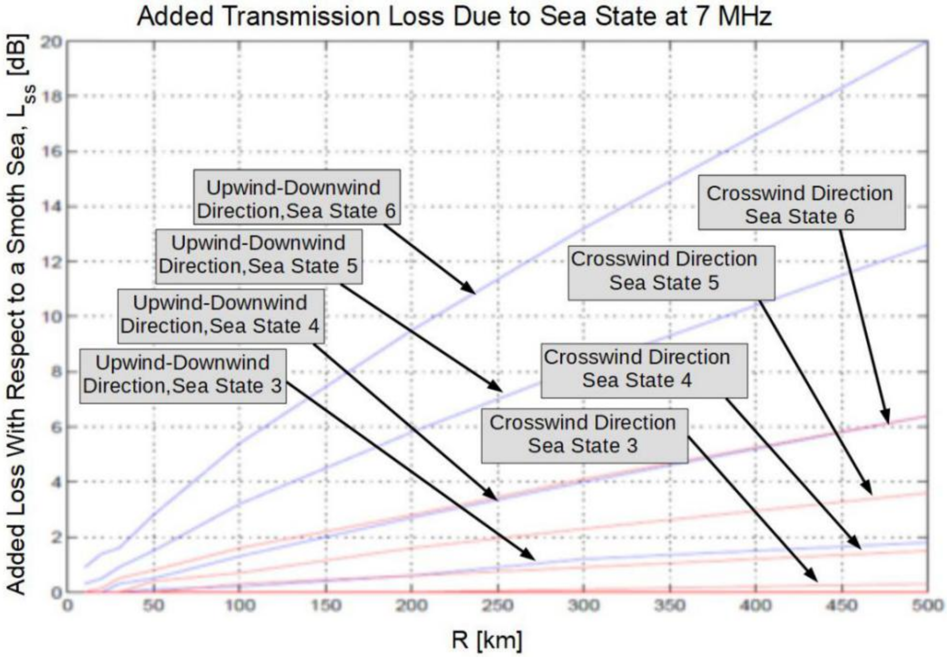


Figure 4 – Model of the signal loss due to roughness of the sea
Рис. 4 – Модель потери сигнала вследствие волнения моря
Слика 4 – Модел губитака у простирању сигнала изнад узбурканог мора

Sub-Model 3: External noise

The main difference for the calculation of the S/N between the MW radar and the HF-OTHR radar is the influence of external noises. For the MW radar, the S/N is defined by thermal noise, while for the OTHR the S/N is significantly affected by the level of external noise in the HF band. External noise consists of various types of noises, such as atmospheric, cosmic, and man - made noise (ITU, 2013).

Atmospheric noise predominantly depends on the geographic location and the season: winter, spring, summer or autumn, while cosmic noise depends only on the time of the day / night. From the HF point of view, there are 6 periods during 24 hours: 00h-04h, 04h-08h, 08h-12h, 12h-16h, 16h-20h, and 20h-24h (Spaulding & Washburn, 1985).

The characteristics of cosmic radio noise are similar to those of thermal noise. Being a phenomenon of the global nature, cosmic noise does not depend on a geographic location or a season. It depends only on the radar working frequency (Skolnik, 1990).

Artificial (man–made) noise varies by regions (rural zones, sub – urban or urban zones). A detailed description of atmospheric and cosmic noise could be found in (Spaulding & Washburn, 1985), while man – made noise mostly depends on the economic development of the area around the radar site, and is thus always analyzed in a very local manner, without a possibility to be covered with a global study. In general, the level of external noise is greater for lower operating frequencies. As shown in (Dzolic et al, 2019a), in some areas man – made noise is absolutely dominant in comparison with other noise sources.

The impact of external noise significantly limits a detection capability of the OTHR radar. The GH-NOISE (Hand, 2017) program is used to calculate the level of noise for different seasons and time of the day. The input for this software is given in the geographical coordinates of a potential radar site, a season, time interval (i.e. time slot, where the duration of the slot is 4 hours) during a day, and operating frequency for calculations.

The output of the GH-NOISE is stored in the form of an TXT file, used further by the Matlab function in order to correlate all types of noises that affect the maximum range of the radar. This function calculates the highest level of all noises (the level of dominant noise for a particular area), during all seasons and predefined time slots, and presents its variation as shown in Figure 5.

The Y axis values represent the noise power above the noise floor (−174 dBm//Hz). According to Figure 5, the average noise level varies between −125 and −112 dBm/Hz. Fam represents the median atmospheric noise power in dB above kTB, DL stands for how many dB below the median noise power exceeded 90% of the days of a month, and DU stands for how many dB above the median noise power exceeded 10% of the days of a month for a particular simulation point (parameter selection).

The value of the Fam is used for the N_0 in equation (1). All values are calculated for a site located in the Gulf of Guinea.

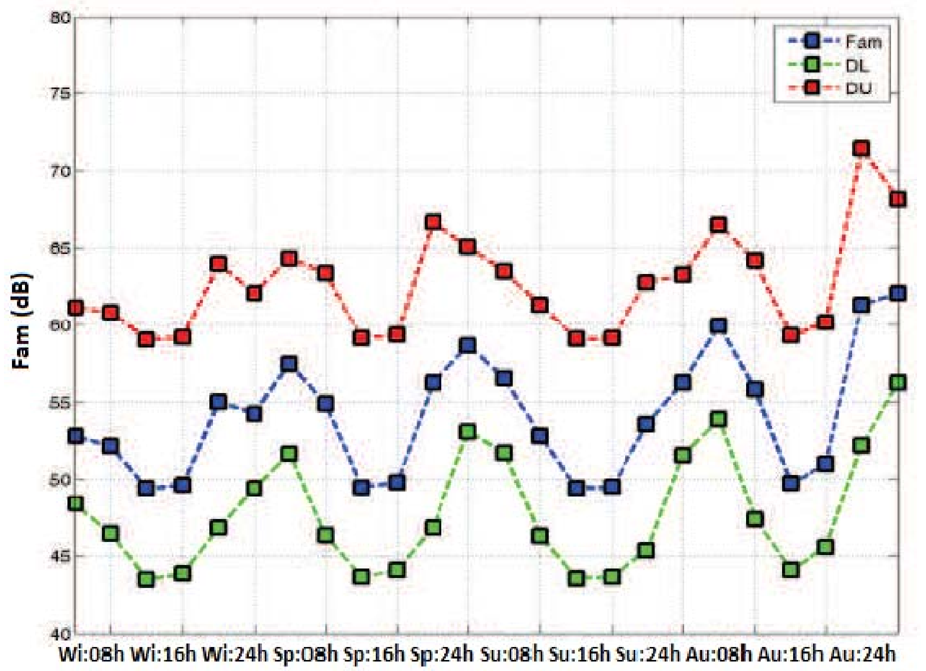


Figure 5 – Model of the external HF noises during all seasons (Wi—Winter, Sp—Spring, Su—Summer and Au—Autumn; 08 h, 16 h and 24 h represents the time of a day; the Y axis values represent the noise power level above the noise floor (−174 dBm/Hz);the values are plotted for 7 MHz operating frequency)
Рис. 5 – Модель внешних „HF“ шумов в течение всех времен года (Wi - зима, Sp - весна, Su - лето и Au - осень; 08 ч, 16 ч. и 24 ч. - время суток; значения по оси Y - уровень мощности шума над шумовым порогом (−174 dBm/Hz); приведены значения рабочей частоты 7 MHz)
Слика 5 – Модел екстерног HF шума током свих годишњих доба (Wi – зима, Sp – пролеће, лето, јесен; 08 ч, 16 ч и 24 ч означавају доба дана; вредности на Y оси представљају ниво снаге шума изнад прага шума (-174 dBm/Hz); вредности су приказане за радну фреквенцију 7 MHz)

Sub-Model 4: Radar cross-section of vessels

One of the most important parameters for the estimation of the radar performance is the RCS. The RCS has influence on the level of reflected signals and determines the signal to noise ratio (SNR). In the phase of the OTHR design, the knowledge about the RCS for different classes of ships is required in order to assess detection and tracking capabilities as objectively as possible. The RCS represents the projected area of a metal sphere that would return the same echo signal as the target does, in case when it would be replaced by the sphere (Skolnik, 1974). The resulting echo from the conductive sphere is independent from the viewing angle, but the echo from a real target varies significantly with spatial orientation of the target (i.e. the angle between the radar and the observed target).

The RCS of the target depends on the following parameters:

- Geometrical shape and size of the vessel exposed to the radar beam,
- Electric properties of the vessel composing materials,
- Target position relative to the incident electromagnetic wave,
- The size of the vessel relative to the wavelength, and
- Antenna polarization with respect to the orientation of the vessel.

The OTHR simulator has the ability to scan the area in the angle width of ±60°around the predefined radar location. In order to detect the target, the receiving signal to noise ratio (SNR) of 10 dB is needed. Along with the OTHR system parameters, the environment parameters that affect detection (month, local time, sea state, man-made noise) are also taken into calculation. The target trajectory is given by target coordinates (latitude and longitude) which change depending on the vessel speed and course. For every point, the radar-vessel incident angle is calculated, which defines the RCS effect, Figure 6.

An analytic method for the calculation of the RCS is only possible for an elementary radar target form, such as a plate, disc, cylinder or thin wire structures. For a complex geometrical form, such as a vessel, analytic methods of the RCS calculation are not feasible. For this reason, professional software for electromagnetic modeling, WIPL-D (Kolundzija, 2005), is used to predict the RCS of vessels. The WIPL-D software enables electromagnetic modeling of antennas and scatters which represent a combination of wired and plate structures. This software uses the Method of Moment (MoM) approach to solve the starting integral equations for the assessment of unknown current distribution. This software solution is mainly used for antenna analysis, but offers a possibility to analyze mono-static and bi-static RCSs.

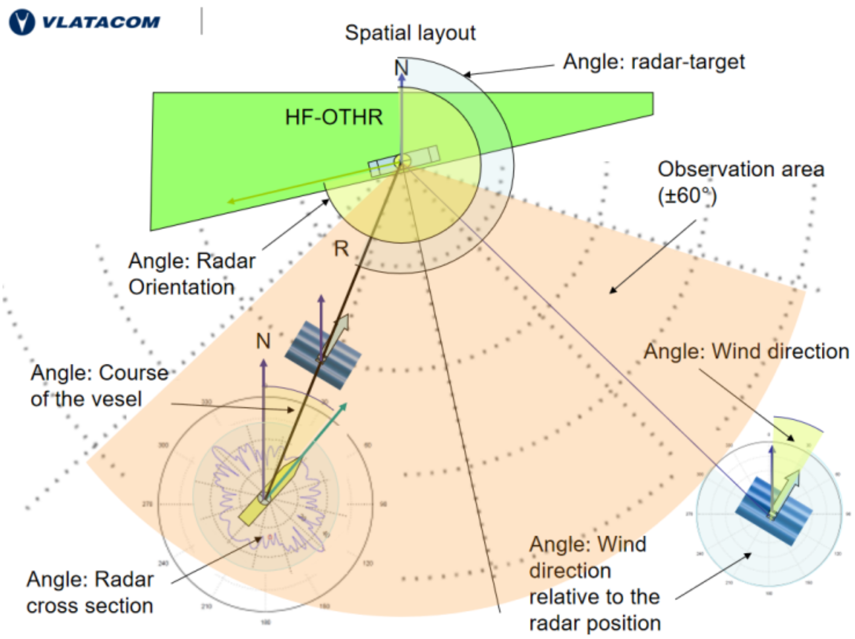


Figure 6 – Impact of the incident angle between the radar and the vessel

Рис. 6 – Влияние угла падения между радаром и судном

Слика 6 – Утицај инцидентног угла између радара и пловила

A model of the RCS implemented in the OTHR Simulator is shown in Figure 7.

This model consists of four important blocks. First of all, for the evaluation of the vessel's RCS, there is an empirical formula that represents a rough approximation only (Wilson & Leong, 2003):

$$\sigma_{RCS} = 52 * f^{\left(\frac{1}{2}\right)} * D^{\left(\frac{3}{2}\right)}, \qquad (3)$$

where *f* is frequency in MHz, and *D* is full-load displacement of the vessel in kilotons. The value σ_{RCS} calculated from this formula represents the maximum value of the RCS related to the vessel size and the working frequency only.

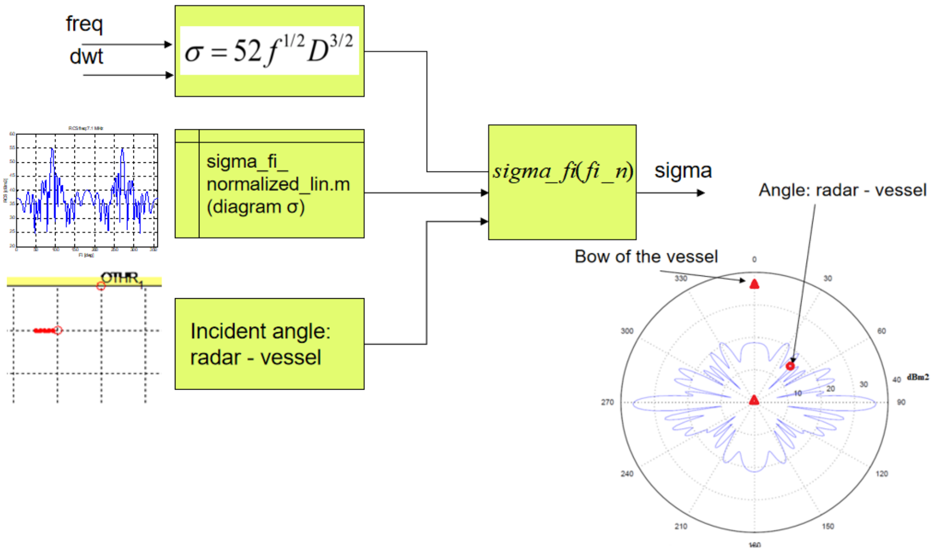


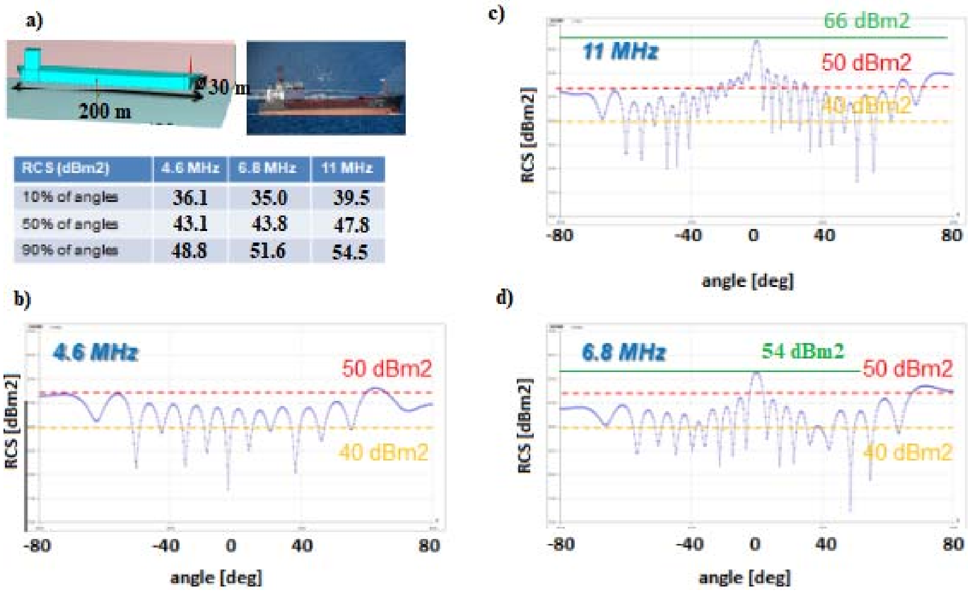
Figure 7 – Model of the radar cross section
Рис. 7 – Модель эффективной отражающей площади
Слика 7 – Модел радарске рефлексне површине

Another block is used for processing the output of the WIPL-D software. The maximum value of the signal is normalized with the signal value calculated by the previous block (empirical formula).

The calculation was made for the operating frequencies of 4.6MHz, 6.8MHz and 11MHz, as shown in Figure 8. The subfigure a) shows a vessel model designed in the WIPL-D and a table with variations due to incident angle change for the abovementioned working frequencies. The subfigures b), c) and d) show the RCS calculated from the WIPL-D for the working frequencies of 4.6MHz, 11 MHz, and 6 MHZ, respectively.

From the subfigure c), one can note that the minimum value of the RCS for the operating frequency of 11MHz, achieved in the situation where an incident wave falls upon the vessel bow, is lower for 26dB from the maximum value.

The highest side-lobes at this operating frequency are around 10dB under the maximum RCS value. For lower frequencies, a difference in the RCS values is smaller.



RCS (dBm2)	4.6 MHz	6.8 MHz	11 MHz
10% of angles	36.1	35.0	39.5
50% of angles	43.1	43.8	47.8
90% of angles	48.8	51.6	54.5

Figure 8 – RCS pattern of a vessel model generated with the OTHR Simulator a) WIPL-D model of the vessels and the table with the results of the RCS values for the simulated vessel, b) RCS calculated at 4.6MHz, c) RCS calculated at 11MHz, and d) RCS calculated at 6.8MHz

Рис. 8 – RCS модель судна, созданная с помощью OTHR симулятора. a)Модель судов WIPL-D и таблица с результатами значений RCS моделируемого судна, b) RCS, рассчитанная на 4,6 MHz, c) RCS, рассчитанная на 11 MHz, и d) RCS, рассчитанная на 6,8 MHz

Слика 8 – RCS расподела модела пловила срачуната помоћу OTHR симулатора. а) Модел пловила WIPL-D и табела са резултатима RCS вредности за симулирани брод, b) RCS израчунат на 4,6 MHz, c) RCS израчунат на 11 MHz и d) RCS израчунат на 6,8 MHz

From the third block (Figure 7), the user defines the incident angle between the radar and the vessel (Dzvonkovskaya & Rohling, 2010). Depending on the incident angle value, the RCS could change significantly, as shown in Figure 7, where the red triangle represents the course of the vessel, while the red circle represents the value of the RCS for the incident angle of the wave transmitted from the radar. From Figure 7, it can be also noticed that the RCS is attenuated for more than 20 dB, relative to the maximum value of the RCS for the incident angle of 90/270°.

The final block of this stage summarizes the values from the outputs of the previous three blocks, and generates a resulting σ_{RCS} value at its output depending on all the previously mentioned parameters. The data obtained within this simulation can be easily exported to various file formats, which allows it to be imported into other software tools for further analysis. The generated RCS value, along with other basic parameters generated by the Simulator's specific blocks, provides a complete set of data necessary for the computer – based simulation of the OTHR.

A sample simulation

The paper presents the emulation of the sample system performances in the actual environment, carried out with the Simulator consisting of the described software components, executed in order to assess the coverage and test the vessel monitoring capabilities of the sample system. The system is fed with carefully prepared sets of inputs, with the aim of optimally illustrating the characteristics of the radar under various parameters in radar's own setup, targets, environment conditions and others. The flowchart of this sample simulation is shown in Figure 9.

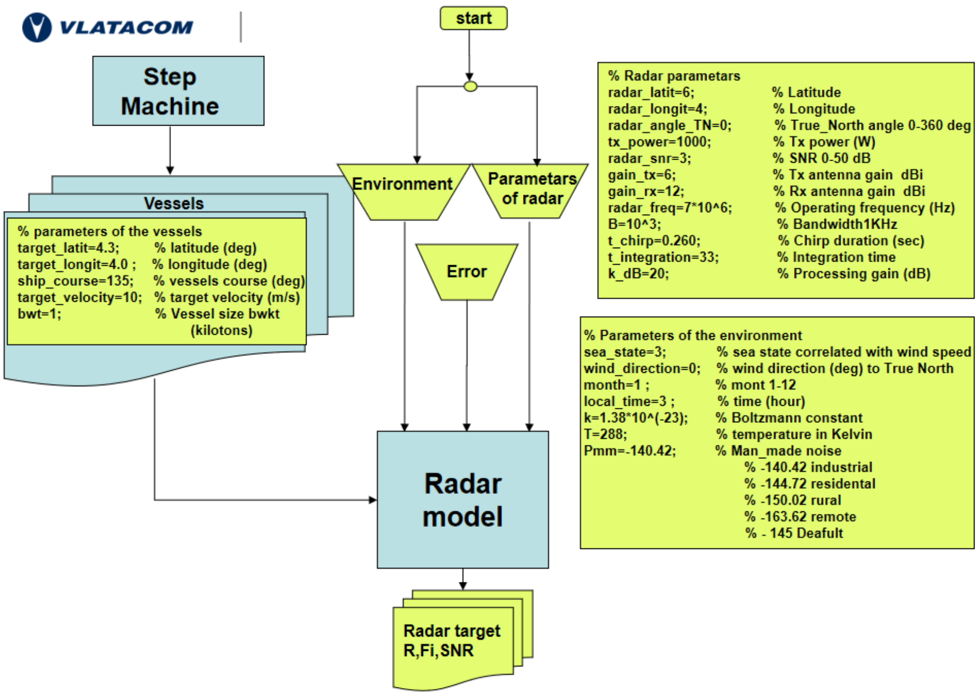


Figure 9 – Flowchart of the OTHR sample simulation
Рис. 9 – Блок-схема OTHR симулятора
Слика 9 – Дијаграм тока OTHR симулатора

Inputs for a simulation

The inputs for the simulation are provided through three important sets of parameters: Parameters of the radar, Environment parameters and Sample vessels. The block named “Error” gives an optional ability to analyze the impact of possible deviations of radar parameters, environment or target positions. A LAT and LON data from the step machine are converted into a radar coordinate system in relation to the LAT and LON positions of the radar in form of the distance (*R*), the angle (F_i), and the S/N corresponding with particular targets.

The distance (R) is used in modules 1 and 2 to calculate losses in the propagation of electromagnetic waves above the sea surface.

Parameters of the radar

The coordinates of the radar site were chosen in order to represent the situation as close as possible to realistic site locations that should be analyzed for potential deployment. Table 1 lists the main parameters of the radar.

Table 1 – Input parameters of the radar
Таблица 1 – Входные параметры радара
Табела 1 – Улазни параметри радара

NO	PARAMETER	UNIT	DEFAULT VALUE	VARIABLE
1	Radar latitude position	°	6.3	*radar_latit*
2	Radar longitude position	°	3.3	*radar_longit*
3	true_north-radar-antenna angle (main beam direction)	°	180	*radar_angle_TN*
4	Transmitted power	W	1000	*Tx_power*
5	SNR	dB	10	*Radar_snr*
6	Tx antenna gain	dBi	6	*gain_tx*
7	Rx antenna gain	dBi	12	*gain_rx*
8	Radar frequency	MHz	4.6	*radar_freq*
9	Bandwidth	kHz	1	*B*
10	Chirp duration	Sec	0.26	*t_chirp*
11	Integration time	Sec	33	*t_integration*

Environment parameters

Table 2 lists the environment parameters considered in the sample simulation.

Table 2 – Inputs for the environment estimation
Таблица 2 – Входные параметры оценки окружающей среды
Табела 2 – Улазни параметри за естимацију окружења

NO	PARAMETER	UNIT	DEFAULT VALUE	VARIABLE
1	Sea state 1-6		1	*sea_state*
2	Wind direction (°) to True North	°	0	*wind_direction*
3	Month 1-12		1	*month*
4	Time (Hour) 0-24		9	*local_time*

Sample vessels

A number of the parameters related to the vessels being directly of interest for the purpose of sample simulation are provided, describing the targets in a particular simulation scenario. These are shown in Table 3.

Table 3 – Input parameters for the sample vessels
Таблица 3 – Входные параметры по пробоотборникам
Табела 3 – Улазни параметри за симулиране бродове

NO	PARAMETER	UNIT	DEFAULT VALUE	VARIABLE
1	latitude (°)	°	5	*target_latit*
2	longitude (°)	°	5	*target_longit*
3	Vessel's course (°) TrueNorth	°	270	*ship_course*
4	Target velocity (m/s)	m/s	10	*target_velocity*
5	Ship size	kT	100	*bwt*

The estimations of the RCS surface used in this simulation, generated for the two system operating frequencies are shown in Table 4

Table 4. The values are classified for three categories of the vessels: Very large - VL, Medium – M, and Very small – VS (each category is defined by gross tones and the physical dimensions of the vessels (Grbić et al, 2018), as indicated in Table 4.

Table 4 – Estimated RCSs for 4.6 MHz and 7MHz, and the vessel size classification
Таблица 4 – Расчетное RCS для 4,6 MHz и 7 MHz и классификация размеров судов
Табела 4 – Процењени RCS за 4,6 MHz и 7 MHz и класификација величине бродова

	Very large – VL	Medium – M	Very small – VS
DWT(1000T)	300	50	5
Length (m)	400	200	50

	Very large – VL	Medium – M	Very small – VS
Width (m)	60	30	10
RCS- 4,6 MHz (m2)	579514.28	39430.95	1246.92
RCS- 4,6 MHz (dBm2)	57.63	45.96	30.96
RCS- 7 MHz (m2)	714881.81	48641.55	1538.18
RCS- 7 MHz (dBm2)	58.54	46.87	31.87

The results of the simulation

Two different scenarios are used to demonstrate the functionality of the described OTHR dedicated Simulator. The results from each simulation are compared with the realistic values achieved on the implemented OTHR system, and the obtained numerical results are forwarded to the presentation software tool for display and analysis.

The first scenario demonstrates the sea state effect on the vessel monitoring process, the second scenario demonstrates the vessel radial movement behavior in the context of detection performance, while the third scenario estimates the positioning error achieved in simulations. All the results are presented and explained, successively.

Scenario #1:Sea state effect on the vessel monitoring process

This scenario aims to show the sea state and the wind direction effect on the general system coverage area considered, for the vessels as defined. The hypothesis that a higher sea state value reduces the coverage of the system is under check with the simulation.

The radar targets in this scenario are created in the form of the group of 3 vessels of different classes. The vessel closest to the radar has the smallest class, while the distance from the radar is the biggest for the largest vessel. The movement of the group is linear, with a constant speed and the course normal to the radar receive array. The distance between successive vessels is fixed at 45 km. The observation zone for the simulation starts at 5km from the radar, and goes to 400km towards the open sea, with the coverage angle of 120° (±60° from the center axis of the radar array).

The scenario setup with the initial positions of the vessels and their bearings is presented in Figure 10. The main goal is to analyze the location of the potential site and, related to that geo-location, the X axis shows relative latitude, while the Y axis shows relative longitude of the observation area.

Integration time, the parameter defined in Table 1, represents the time needed for the radar simulator to complete acquisition of the data. Since the real radar takes 33s for the integration time, in this scenario the integration time will be set to 33s exactly. Chirp duration defined in Table 1 is 0.26s. For this scenario, 256 chirps are used, which represents a total simulation duration time of around 66s (0.26s *256). In total, eight data runs are executed: for each working frequency (2 data runs) and for each sea state (4 data runs) considered. Here, the considered sea state values are 1, 3, 5, and 6, with the vessel sizes of VS, M, VL observed in each simulation run. The operating frequencies considered are 4.6 MHz and 7 MHz.

The parameters for the sea state, the wind direction, the time of the year and the time of the day are defined in Table 2 and taken into account to calculate the maximum range of the detected targets. The "wind direction" parameter has a fixed value in all simulations.

The outputs of the radar simulator for scenario #1 are given in Table 5. The column "Expected Range" represents the values acquired from the previously installed (operational) radars in the field, while the "Actual Range" represents the values from the output of the OTHR simulator for a specific location. As it can be noticed from Table 5, the achieved results show that a higher sea state reduces the coverage of the OTHR system, as expected.

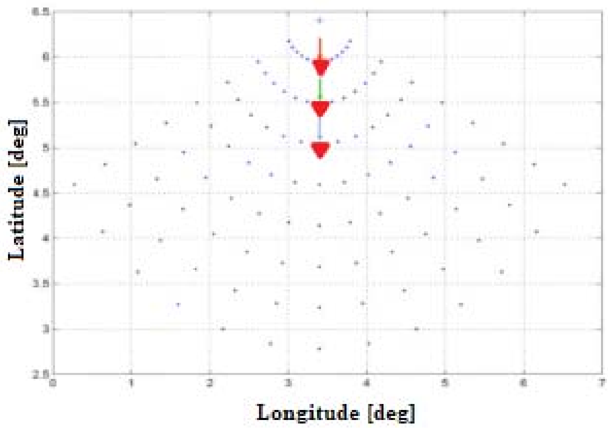


Figure 10 – Initial setup of scenario #01, the initial positions of the sample vessels are marked with coloured arrows.
Рис. 10 – Первоначальная настройка сценария № 01, начальные положения проботборников отмечены цветными стрелками.
Слика 10 – Иницијална поставка сценарија #01(почетне позиције пловила означене су обојеним стрелицама)

Table 5 – Achieved results for the analysis of the sea state effect on the vessel monitoring process, all range values presented in km units
Таблица 5 – Полученные результаты для анализа влияния состояния моря на процесс мониторинга судов, все значения приведены в км

Табела 5 – Постигнути резултати анализе утицаја стања мора на процес праћења пловила(све вредности су приказане у километрима)

Case	Radar freq. MHz	Sea State	Expected Range for **VS vessel**	Actual Range for **VS vessel**	Expected Range for **M vessel**	Actual Range for **M vessel**	Expected Range for **VL vessel**	Actual Range for **VL vessel**
1	4.6	1	215	222.75	300	313.25	370	387.75
2	4.6	3	215	225.75	300	317.25	370	392.75
3	4.6	5	190	197.25	260	275.75	320	340.25
4	4.6	6	170	176.25	220	245.75	280	302.75
5	7	1	120	129.75	180	196.25	240	253.25
6	7	3	115	127.75	160	191.25	230	245.25
7	7	5	100	103.75	140	154.75	180	197.75
8	7	6	90	92.25	120	135.25	160	172.75

From the columns “Actual Range” and “Expected Range” it can be noticed that the values for the maximum achieved range achieved via the simulation are very similar to those expected from the practical radar performance, and some existing small variations directly depend on the difference in the values of system parameters, as defined for the specific location.

Scenario #2: Vessel radial movement impact on the detection performance

In this scenario, the coverage area is observed for the vessels that are moving away from the radar, radially with a radiation pattern of the radar array, and with a difference between their courses of 10°. The hypothesis under check with this simulation is: that the achieved radar detection range is higher at the central lobe of the antenna array than at its boundaries, while the detection range for particular vessels varies depending on the size and working frequency (larger the vessel - higher the range, and lower the frequency - higher the range will be).

Figure 11 presents the initial positions of the vessels and their bearings for scenario #2.

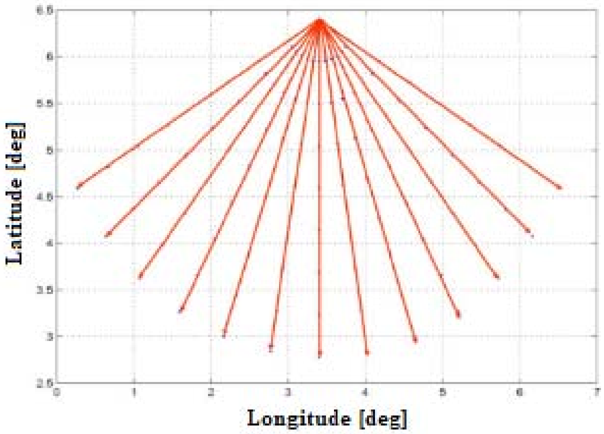


Figure 11 – Initial setup of scenario #02, the vessel trajectories presented with red lines
Рис. 11 – Начальная настройка сценария #02, траектории судна обозначены красными линиями
Слика 11 – Иницијална поставка сценарија #02(путање бродова приказане су црвеним линијама)

The radar targets are created in a form of the group of 13 vessels of the same classes, per one simulation run, while 3 different classes of vessels for different simulation runs will be demonstrated. The movement of the group is linear with a constant speed and course, radial to the radar receive array (radiation pattern). The observation zone for the simulation starts 5 km from the radar itself, and goes to 400 km towards the open sea, with the coverage angle of 120° (±60° from the center axis of the radar array).

The integration time is set to 33s, while the total duration time of the simulation is around 66s (in accordance with the comments already given for the previous scenario, above). In total, six data runs will be executed: for each working frequency (2 data runs) and for each class of the vessel (3 data runs) observed. The considered sea state value is 3, with the vessel sizes of VS, M, VL considered in each simulation run. The operating frequencies considered are 4.6 MHz and 7 MHz.

The resulting outputs of the radar simulator for scenario #2 are given in Table 6 and Table 7. The results are presented only for sectors 1-7 (corresponding with the angles from 60° down to 0°, with a decrement of 10°), since the values achieved in sectors 8-13 (corresponding with the angles from 0° up to -60°, with a decrement of 10°) are completely symmetrical with the ones presented. The ranges are given in km, where the fields marked with the letter “E” (Expected) represent the predicted values from the output of the OTHR radar, based on the values from the previously installed (operational) radars, while the values marked with “A” (Actual) represent the values from the output of the OTHR simulator, for the considered, specific location.

Table 6 – Achieved maximum detection range in the scenario with the vessel radial movement, for the radar operating frequency of 4.6 MHz, all values presented in km units
Таблица 6 – Достигнута максимальная дальность обнаружения в сценарии с радиальным движением судна при рабочей частоте радара 4,6 MHz, все значения приведены в км
Табела 6 – Постигнути максимални домет детекције у сценарију са радијалним кретањем пловила за радну фреквенцију 4,6 MHz (све вредности су приказане у километрима)

Vessel size \ Sector	1E	1A	2E	2A	3E	3A	4E	4A	5E	5A	6E	6A	7E	7A
VS	180	188.2	185	189.2	195	202.2	200	209.7	205	218.7	215	221.7	220	222.7
M	275	276.2	280	289.2	290	299.2	295	304.7	300	309.7	305	311.7	310	312.7
VL	330	343.7	350	363.2	360	368.2	370	374.2	380	380.2	385	387.2	385	388.2

As it can be noticed from Table 6 and Table 7, the larger vessels are visible at greater distances from the radar, in comparison with smaller classes of vessels, as expected. Also, the vessels of the same size are visible at greater distances when detected with a lower operating frequency (4.6MHz) of the radar system. The absolute maximum range is achieved in the direction of the center axis of the radar array, while, by moving away from the direction of the angle center, the maximum range value decreases.

Table 7 – Achieved maximum detection range in the scenario with the vessel radial movement, for the radar operating frequency of 7 MHz, all values presented in km units
Таблица 7 – Достигнута максимальная дальность обнаружения в сценарии с радиальным движением судна при рабочей частоте радара 7 MHz, все значения прприведены в км
Табела 7 – Постигнути максимални домет детекције у сценарију са радијалним кретањем пловила за радну фреквенцију 7 MHz (све вредности су приказане у километрима)

Vessel size \ Sector	1E	1A	2E	2A	3E	3A	4E	4A	5E	5A	6E	6A	7E	7A
VS	90	106.7	95	114.7	110	124.7	115	127.7	120	128.7	125	129.7	125	129.7
M	160	168.7	170	177.7	180	187.2	185	191.2	190	192.2	195	195.2	195	195.2
VL	215	223.7	225	234.7	230	241.7	235	247.7	240	250.7	250	252.2	250	253.2

By comparing the columns “E” and “A”, it can be noticed that the OTHR simulator confirms the predicted ranges in a reasonable manner, and the variations that exist in the compared values directly depend on the input parameters (external noises) related to the specific location where the radar could be installed. Still, the magnitudes of detection range values for particular vessel classes, and the tendencies in their dynamics are simulated with proper correctness. This result represents another important confirmation of a proper performance of the developed Simulator, in terms of its practical usability.

Conclusion

In this paper, we presented a solution for the OTHR Simulator, based on software models for radar propagation and executed on a standard COTS computer. The solution is described in detail, and tested under characteristic parameters that verify its basic functionality and illustrate the properties of data achieved through the simulation. It was shown that the simulator allows the analysis of the environmental impact on the operation of OTHR radars, along with an impact of various system–specific parameters. The solution is flexible in possible interfacing with other computer–based tools, along with the real radar equipment for the comparison of the acquired data and a potential comparison for the purpose of real–system tuning. The Simulator solution was tested under various scenarios, with the aim to check its basic functionality, but also to make relevant comparisons of simulations with realistic measurements acquired in the field, from operational OTHR radars. As it was clearly shown, the achieved simulation results not only apply to the expected theoretical behavior, but also fit in quite a reasonable manner with the real data, thus confirming that the reliability of the simulations is at the level properly high for practical considerations. After the comprehensive tests, it may be concluded that the proposed simulator shows high reliability and represents an effective tool for the analysis and OTHR system planning, in spite of its simplicity in structure.

The implemented software solution of the OTHR Radar Simulator has enabled the further development of algorithms at a higher level of radar signal processing, like detection and tracking software. Also, various scenarios have been used with this Simulator for testing the capabilities of OTHR radars in real deployment. This was done by engineers in the Vlatacom Institute for the vHF-OTHR system installations on several locations worldwide, and the gained experience in assessing the real capabilities of OTHR radar systems was provided for practical purpose. Finally, the described software solution can be used not only for research & development of radar systems, or for commercial applications strictly, but also for teaching purposes at higher education institutions which are covering the field of radar systems.

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РАЗРАБОТКА СИМУЛЯТОРА ЗАГОРИЗОНТНОГО РАДИОЛОКАТОРА

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РУБРИКА ГРНТИ: 47.00.00 ЭЛЕКТРОНИКА. РАДИОТЕХНИКА:
47.49.00 Радиотехнические системы зондирования, локации и навигации,
47.49.29 Радиолокационные системы, станции

ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Симулятор загоризонтного радиолокатора, представленный в этой статье, разработан и используется на практике с целью имитации среды радиолокационного сигнала, а также для оптимизации параметров радара в реальном применении, таких как: излучаемая мощность, усиление антенной решетки, потери при передаче, эффективная отражающая площадь, внешние помехи и шумы.

Методы: В данной статье применен метод математического моделирования и симуляции.

Результаты: На основании проведенного анализа в статье представлены выходные данные симулятора загоризонтного радиолокатора.

Выводы: Применение описанного симулятора загоризонтного радиолокатора позволяет автоматизировать прогноз возможности использования радара на потенциальных локациях, при этом результаты симуляции превосходно согласованы с реальными данными.

Ключевые слова: загоризонтный радиолокатор, эффективная отражающая площадь, исключительная экономическая зона, симулятор радара.

ЈЕДНО РЕШЕЊЕ СИМУЛАТОРА ИЗАХОРИЗОНТСКОГ РАДАРА

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ОБЛАСТ: електроника, телекомуникације
ВРСТА ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Симулатор изахоризонтског радара (ИХР), који је представљен у овом раду, развијен је и коришћен у пракси, са циљем да опонаша окружење радарског сигнала, али и да оптимизира параметре радара у стварној примени, као што су: зрачена снага, појачање антене, губитак пута, радарска рефлексна површина, спољне сметње и шум.

Методе: У раду се користи методологија математичког моделирања и симулација.

Резултати: На основу обављене анализе, излазни подаци из ИХР симулатора представљени су и разматрани.

Закључак: Примена описаног симулатора ИХР омогућава аутоматизовану процену могућности употребе радара на потенцијалним локацијама, док резултати симулације показују високо слагање са реалним подацима.

Кључне речи: изахоризонтски радар, радарска рефлексна површина, ексклузивна економска зона, радарски симулатор.

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