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МЕТОДИ АНАЛІЗУ ТА УПРАВЛІННЯ СИСТЕМАМИ В УМОВАХ РИЗИКУ І НЕВИЗНАЧЕНОСТІ

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METHOD OF POLARIZATION SELECTION OF NAVIGATION OBJECTS IN ADVERSE WEATHER CONDITIONS USING STATISTICAL PROPERTIES OF RADIO SIGNALS

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Abstract. This research article is devoted to studying and applying polarization selection for navigation objects in difficult atmospheric conditions. It provides a novel application of Stokes parameters in radar signal processing for navigation objects, validated by experimental data. The main emphasis is on using the statistical properties of the polarization parameters of partially polarized echo signals. The article discusses in detail the statistical properties of the polarization parameters of partially polarized echo signals, which can be used to improve the accuracy of ship radiolocation systems. The study is based on analyzing experimental data collected in various atmospheric conditions. The results indicate the effectiveness of polarization selection in improving the stability and accuracy of radar navigation systems in various atmospheric conditions. The use of statistical methods allows the navigation system to adapt to changing conditions, ensuring reliability in different scenarios. Polarization selection based on the statistical properties of polarization parameters is a promising method to improve navigation in high atmospheric humidity, fog, and other complex atmospheric conditions. It can be used in the development of modern navigation systems.

Keywords: safety of navigation, atmospheric conditions, statistical properties, partially polarized, echo signals, radar systems, navigation equipment, bridge resources, maritime transport, radiolocation, ship handling and maneuvering.

INTRODUCTION

Over the past decades, high-precision navigation systems have become critical for a wide range of applications, including autonomous vehicles, unmanned aerial vehicles, maritime navigation, and others. However, the effectiveness of these systems can be significantly reduced in difficult atmospheric conditions. The development of new methods that ensure stable and efficient navigation in such conditions is an urgent problem. Thus, the growing need for high-precision radio navigation systems requires the development of new methods to ensure stable and efficient navigation in various atmospheric conditions. In this context, polarization selection of navigation objects seems to be a promising research direction. Polarization selection is becoming an object of active research to solve these problems. This method is based on the use of statistical properties of polarization parameters of echo signals of partially polarized waves. Light polarization has the potential to improve signal quality and ensure navigation stability in conditions of limited visibility and atmospheric instability.

The literature review encompasses a range of topics related to radar systems, maritime navigation, and signal processing. The discussed works address the issues of ship radar systems, construction of modern high-precision intelligent control systems for marine vessels [1], navigation support for ship traffic control [2], analysis of prediction methods for determining the parameters of ship equipment [3; 4]. In addition, the issues of modeling of radar signals for objects of complex spatial configuration [5] and scattering of electromagnetic waves by radar objects [6] are investigated.

The paper [7] contributes insights into the selection of radar signals from navigation objects in the presence of atmospheric formations. Other works cover constraints on spatial measurements in phased-array radar due to atmospheric effects [9], radar detection and identification methods for objects with resonant sizes [8], and the influence of propagation medium on maritime direction measurements [10–13], address challenges in measuring the range of low-altitude targets within the tropospheric waveguide over the sea and the measurement of the Doppler frequency of signals reflected from targets beyond the radio horizon over the sea.

In [14], a comparison of ship radars operating in different frequency bands was made. The comprehensive manual on radar, AIS, and target tracking for marine radar users presented in [15]. The work [16] examined the suitability of ARPA for the automatic assessment of AIS targets. In [17] discussed ways to enhance awareness of maritime situations through the integration of shipborne radars, [18] explores radars for maritime domain awareness.

In [19; 20] provided essential information on radar technology and the challenges in the public administration of autonomous shipping, respectively. The article [21] addresses multi-level challenges in the public administration of navigation safety. Sources [22–30], cover various aspects of maritime safety, vessel operational efficiency, vulnerability assessment, information security, environmental efficiency, fuzzy controllers in vessel motion control and energy efficient motion modes contributing significantly to the understanding of modern maritime operations, safety and technology.

The references [31–43] contribute to the understanding and improvement of maritime transportation and navigation process safety. These studies cover aspects such as public safety management, maritime situational awareness, vessel equipment vulnerability assessment, vessel information security risks, maritime transportation security, autonomous vessels, vessel traffic management systems and energy efficient modes of propulsion systems. They provide valuable insights into maritime safety issues and developments, offering potential solutions and improvements for safe navigation [44; 45] in different conditions.

Thus the methodology proposed in this paper provides a comprehensive and data-driven approach to solving problems related to polarization selection. Through a thorough literature review, the approach seamlessly integrates statistical analysis, radar measurements, and practical considerations, offering a sound basis for effective navigation decision making. Synthesizing these elements not only improves the understanding of polarization selection methods, but also makes a valuable contribution to the improvement of shipboard radar systems in various atmospheric conditions.

MATERIALS AND METHODS

Safe navigation is of paramount importance to ensure the integrated safety of maritime operations. Ship handling and maneuvering in challenging atmospheric conditions require accurate and reliable navigation systems. Ship radar, being a cornerstone of maritime navigation technology, relies on advanced polarization techniques to accurately detect and analyze echo signals. The utilization of polarimetric data in radar systems enhances the precision of object identification, providing critical information for safe ship handling and maneuvering. By integrating polarimetric insights into radar technology, maritime operators gain a more comprehensive understanding of their surroundings, enabling proactive measures for collision avoidance and ensuring a higher level of safety in challenging atmospheric conditions.

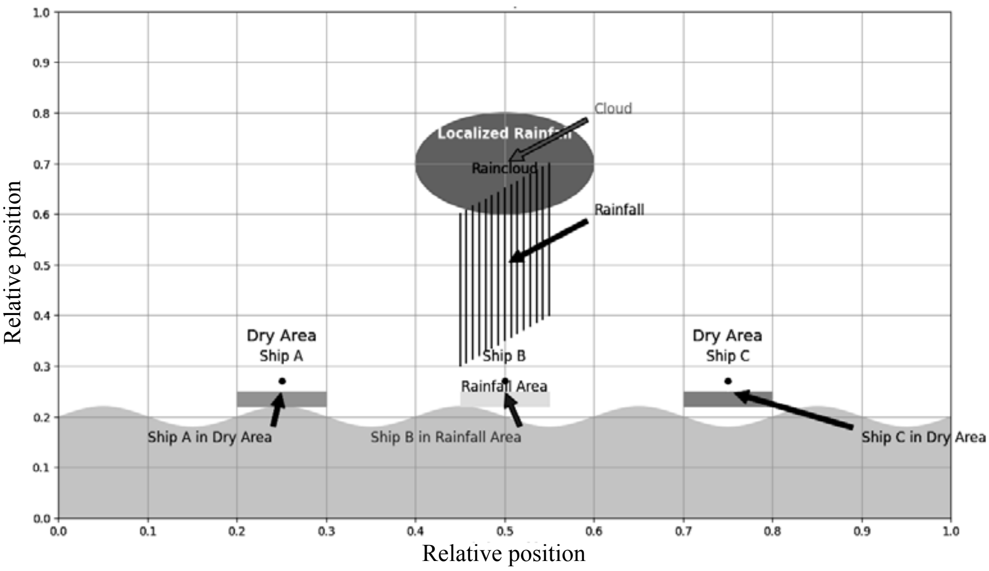
Practical use of polarization parameters of electromagnetic wave in shipboard radar polarization complexes (SRPC) in solving the problem of polarization selection of navigation objects located in difficult conditions atmospheric environment on the way of the ship, due to the need to use microwave elements and antenna devices that allow radiation with subsequent analysis of their polarization parameters. The following antenna devices were used as the SRPC antenna an omnipolarized antenna with controlled polarization to radiation, which allows to optimally realize the energy capabilities of SRPC by representing polarization by real energy Stokes parameters.

During the radar observation of navigation objects against the background of atmospheric formations, the echo signals arriving at the input of the SRPC receiver will be reflections from a complex object. Assuming that the Stokes vector of a complex object has normally distributed components in an arbitrary basis, the one-dimensional law of distribution of the Stokes parameters of the navigation object and the atmospheric formation is used to determine the properties of the echo signal of a complex object received at the SRPC input. The Stokes energy parameters are quadrature with respect to the field strength of a partially polarized electromagnetic wave and uniquely determine its polarization. To fully determine the probability density of the Stokes parameters of the echo signal of a partially polarized electromagnetic wave scattered by a complex object, it is necessary to calculate their mean values, variances, and standard deviations.

To address the challenge of polarization selection for navigation objects amidst atmospheric formations, statistical properties of Stokes parameters of partially polarized electromagnetic waves from the complex object's lunar signals were utilized. Solving the specified task involves the incorporation of a priori information characterizing objects of radar observation systems. This a priori information encompasses the number of observed atmospheric formations (precipitation of varying intensity) that create erroneous markers on the radar indicator. Additionally, it includes a set of features describing the observed objects, as well as the probability distribution laws of the feature set.

The set of features that characterize the recognized objects are the energy polarization parameters of Stokes, which form the predictor, whose components are the Stokes parameters themselves (S_1, S_2, S_3, S_4). The probabilistic characteristics of the predictor $\overline{S}$ are the laws of distribution of the Stokes parameters of the navigation object and the atmospheric formation.

The echo signals of a navigation object are equivalent to the presence of a polarized component in the echo signal of the total partially polarized wave of a complex object. The fluctuating component of the echo signal of the total partially polarized wave of a complex object caused by reflection from an atmospheric formation corresponds in its statistical properties to the echo signal of a partially polarized wave subject to the central limit theorem of probability theory. In the case of a navigation object in the area of an atmospheric formation (Figure), the reflection of an electromagnetic wave irradiating two objects (a complex object) with different electrical conductivity (metal and water in liquid or solid state) at the same time is equivalent to the presence of a polarized component (navigation object) and a fluctuating component (atmospheric formation).



Radar observation of a navigation object against the background of an atmospheric formation

When receiving an echo signal of a partially polarized electromagnetic wave simultaneously from two objects (a complex object), all four Stokes parameters are recorded simultaneously, and their criterion values are set based on the values. At the same time, for a navigation object, polarization selection of its echo signals is performed against the background of echo signals from an atmospheric formation.

To solve the problem of polarization selection of echo signals of a navigation object, the laws of distribution of predictors are used $W(\overline{S}/HO)$ navigation object and $W(\overline{S}/AU)$ of the atmospheric formation, which in the theory of recognition are functions of the probability of the feature vectors of predictors $\overline{S}$, which will include the Stokes parameters of the navigation object and the atmospheric formation. These laws show the probability of forming predictors $\overline{S}$ з with given values of the Stokes parameters, provided that the echo signals are generated by the navigation object and the atmospheric formation, and the distribution of the reflectivity of the predictors $\overline{S}$ can be described by normal laws. Since these predictor $\overline{S}$ distribution laws intersect, the problem of polarization selection of the navigation object is solved using the maximum likelihood rule, which is defined by the following inequality:

$$\frac{W(S_n/HO)}{W(S_n/AO)} \geq 1\,. \quad (1)$$

Expression (1) for the four Stokes parameters of the echo signal of a partially polarized wave is written as follows:

$$\frac{W(S_1/HO)}{W(S_1/AO)} \geq 1, \quad \frac{W(S_2/HO)}{W(S_2/AO)} \geq 1, \quad \frac{W(S_3/HO)}{W(S_3/AO)} \geq 1, \quad \frac{W(S_4/HO)}{W(S_4/AO)} \geq 1. \quad (2)$$

Since the reflectivity distribution of the Stokes parameters can be described by normal laws, then inequalities (2) are given in the form:

$$\frac{W(S_1/HO)}{W(S_1/AU)} = \frac{\frac{1}{\sqrt{2\pi}\sigma_{HO}} e^{-\frac{(S_1 - m_{HO})^2}{2\sigma^2_{HO}}}}{\frac{1}{\sqrt{2\pi}\sigma_{AU}} e^{-\frac{(S_1 - m_{AO})^2}{2\sigma^2_{AO}}}}; \quad \frac{W(S_2/HO)}{W(S_2/AU)} = \frac{\frac{1}{\sqrt{2\pi}\sigma_{HO}} e^{-\frac{(S_2 - m_{HO})^2}{2\sigma^2_{HO}}}}{\frac{1}{\sqrt{2\pi}\sigma_{AU}} e^{-\frac{(S_2 - m_{AO})^2}{2\sigma^2_{AO}}}};$$

$$\frac{W(S_3/HO)}{W(S_3/AU)} = \frac{\frac{1}{\sqrt{2\pi}\sigma_{HO}} e^{-\frac{(S_3 - m_{HO})^2}{2\sigma^2_{HO}}}}{\frac{1}{\sqrt{2\pi}\sigma_{AU}} e^{-\frac{(S_3 - m_{AO})^2}{2\sigma^2_{AO}}}};$$

$$\frac{W(S_4/HO)}{W(S_4/AU)} = \frac{\frac{1}{\sqrt{2\pi}\sigma_{HO}} e^{-\frac{(S_4 - m_{HO})^2}{2\sigma^2_{HO}}}}{\frac{1}{\sqrt{2\pi}\sigma_{AU}} e^{-\frac{(S_4 - m_{AO})^2}{2\sigma^2_{AO}}}}, \quad (3)$$

where S_1, S_2, S_3, S_4 — measured Stokes parameters of a complex SRPC observation object; σ_{HO}, σ_{AU} — statistical parameter — the standard deviation for the general population of a series of observations of the Stokes parameters of the navigation object and the atmospheric formation, respectively; m_{HO}, m_{AU} — statistical parameter — mathematical expectations of the Stokes parameters of the echo signals of the navigation object and the atmospheric formation, respectively; $\sigma^2_{HO}, \sigma^2_{AU}$ — statistical parameter — the variances of the Stokes parameters of the echo signals of the navigation object and the atmospheric formation, respectively.

Transforming the right-hand side of equations (3) according to the expression for the exponential function $e^{a+b} = e^a - e^b = \frac{e^a}{e^b}$ allows us to obtain the following dependencies for the right-hand side of the distribution laws of the predictor of the navigation object and the atmospheric formation.

To provide a comprehensive understanding of the underlying physics, we include the mathematical model that relates the Stokes parameters of the electromagnetic wave to the radar object's properties. The Stokes parameters (S_1, S_2, S_3, S_4) describe the polarization state of an electromagnetic wave and are derived from the electric field components. The reflected signals can be represented as the result of the interaction of the electromagnetic wave with the target, possessing certain radar characteristics. The Stokes parameters can be expressed through the target characteristics as follows:

Total power of the wave S_1 related to the reflection coefficient R of the target:

$$S_1 = E_i^2 R\,,$$

where E_i^2 is the amplitude of the incident wave.

Horizontal and vertical polarizations are related to the scattering components R_h and R_v:

$$S_2 = E_i^2 (R_h - R_v)\,.$$

Polarization at 45° and –45°:

$$S_2 = E_i^2 (R_{45} - R_{-45})\,,$$

where R_{45} and R_{-45R} are the scattering components at 45° and –45° respectively

Right-hand and left-hand circular polarizations:

$$S_3 = E_i^2 (R_{rcp} - R_{lcp})\,,$$

where R_{rcp} and R_{lcp} are the scattering components of right-hand and left-hand circular polarization respectively.

Considering the statistical properties of the Stokes parameters, the maximum likelihood method can be applied to determine the target parameters. The probability of the measured values of the Stokes parameters S_i for a target and atmospheric conditions can be written as:

$$P(S_i \theta) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(S_i - \mu)^2}{2\sigma^2} \right),$$

where θ represents the target parameters, and μ and σ are the mean and standard deviation of the Stokes parameters respectively.

The Stokes parameters (S_1, S_2, S_3, S_4) are derived from the received radar signals by first decomposing the signals into their horizontal (E_H) and vertical (E_V) components using polarimetric radar techniques. The Stokes parameters are then calculated using the following relations of magnitudes of the horizontal and vertical components of the electric field, respectively and the complex conjugate product of these components, which captures the cross-polarization information.

The derived Stokes parameters are then used in the statistical decision-making process to determine the presence of a radar target. This involves applying the maximum likelihood rule and evaluating the probability densities of the Stokes parameters for both the navigation object and the atmospheric formations. By following these steps, the radar system can effectively differentiate between the echo signals of navigation objects and atmospheric formations, enhancing the accuracy and reliability of radar-based navigation in challenging conditions.

These parameters are subsequently used in the statistical decision-making process, applying the maximum likelihood rule to evaluate the probability densities and determine the presence of a radar target amidst atmospheric formations.

Let us transform the right-hand side of the equation for the first Stokes parameter and obtain:

$$\frac{\frac{1}{\sqrt{2\pi}\sigma_{HO}}e^{-\frac{(S_1-m_{HO})^2}{2\sigma^2_{HO}}}}{\frac{1}{\sqrt{2\pi}\sigma_{AU}}e^{-\frac{(S_1-m_{AU})^2}{2\sigma^2_{AU}}}}=\frac{\sigma_{AU}\,e^{-\frac{(S_1-m_{HO})^2}{2\sigma^2_{HO}}}}{\sigma_{HO}\,e^{-\frac{(S_1-m_{AU})^2}{2\sigma^2_{AU}}}}=$$

$$=\frac{\sigma_{AU}}{\sigma_{HO}}e^{\frac{(\sigma^2_{HO}-\sigma^2_{AU})}{2\sigma^2_{HO}\sigma^2_{AU}}S_1^2+\frac{(\sigma^2_{AU}m_{HO}-\sigma^2_{HO}m_{AU})}{\sigma^2_{HO}\sigma^2_{AU}}S_1+\frac{(\sigma^2_{HO}m^2_{AU}-\sigma^2_{AU}m^2_{HO})}{2\sigma^2_{HO}\sigma^2_{AU}}}\geq 1; \qquad (4)$$

Similar results are obtained for the second, third, and fourth Stokes parameters:

$$\frac{\frac{1}{\sqrt{2\pi}\sigma_{HO}}e^{-\frac{(S_2-m_{HO})^2}{2\sigma^2_{HO}}}}{\frac{1}{\sqrt{2\pi}\sigma_{AU}}e^{-\frac{(S_2-m_{AU})^2}{2\sigma^2_{AU}}}}=\frac{\sigma_{AU}\,e^{-\frac{(S_2-m_{HO})^2}{2\sigma^2_{HO}}}}{\sigma_{HO}\,e^{-\frac{(S_2-m_{AU})^2}{2\sigma^2_{AU}}}}=$$

$$=\frac{\sigma_{AU}}{\sigma_{HO}}e^{\frac{(\sigma^2_{HO}-\sigma^2_{AU})}{2\sigma^2_{HO}\sigma^2_{AU}}S_1^2+\frac{(\sigma^2_{AU}m_{HO}-\sigma^2_{HO}m_{AU})}{\sigma^2_{HO}\sigma^2_{AU}}S_1+\frac{(\sigma^2_{HO}m^2_{AU}-\sigma^2_{AU}m^2_{HO})}{2\sigma^2_{HO}\sigma^2_{AU}}}\geq 1; \qquad (5)$$

$$\frac{\frac{1}{\sqrt{2\pi}\sigma_{HO}}e^{-\frac{(S_3-m_{HO})^2}{2\sigma^2_{HO}}}}{\frac{1}{\sqrt{2\pi}\sigma_{AU}}e^{-\frac{(S_3-m_{AU})^2}{2\sigma^2_{AU}}}}=\frac{\sigma_{AY}\,e^{-\frac{(S_3-m_{HO})^2}{2\sigma^2_{HO}}}}{\sigma_{HO}\,e^{-\frac{(S_3-m_{AU})^2}{2\sigma^2_{AU}}}}=$$

$$=\frac{\sigma_{AU}}{\sigma_{HO}}e^{\frac{(\sigma^2_{HO}-\sigma^2_{AU})}{2\sigma^2_{HO}\sigma^2_{AU}}S_1^2+\frac{(\sigma^2_{AU}m_{HO}-\sigma^2_{HO}m_{AU})}{\sigma^2_{HO}\sigma^2_{AU}}S_1+\frac{(\sigma^2_{HO}m^2_{AU}-\sigma^2_{AU}m^2_{HO})}{2\sigma^2_{HO}\sigma^2_{AU}}}\geq 1; \qquad (6)$$

$$\frac{\frac{1}{\sqrt{2\pi}\sigma_{HO}}e^{-\frac{(S_4-m_{HO})^2}{2\sigma^2_{HO}}}}{\frac{1}{\sqrt{2\pi}\sigma_{AU}}e^{-\frac{(S_4-m_{AU})^2}{2\sigma^2_{AU}}}}=\frac{\sigma_{AU}\,e^{-\frac{(S_4-m_{HO})^2}{2\sigma^2_{HO}}}}{\sigma_{HO}\,e^{-\frac{(S_4-m_{AU})^2}{2\sigma^2_{AU}}}}=$$

$$= \frac{\sigma_{AU}}{\sigma_{HO}} e^{\frac{(\sigma_{HO}^2 - \sigma_{AU}^2)}{2\sigma_{HO}^2\sigma_{AU}^2}S_1^2 + \frac{(\sigma_{AU}^2 m_{HO} - \sigma_{HO}^2 m_{AU})}{\sigma_{HO}^2\sigma_{AU}^2}S_1 + \frac{(\sigma_{HO}^2 m_{AU}^2 - \sigma_{AU}^2 m_{HO}^2)}{2\sigma_{HO}^2\sigma_{AU}^2}} \geq 1. \quad (7)$$

Let us denote the statistical parameters of degree e in equations (4)–(7) by the coefficients l_1, l_2, l_3 i.e:

$$l_1 = \frac{(\sigma_{HO}^2 - \sigma_{AU}^2)}{2\sigma_{HO}^2\sigma_{AU}^2}; \quad l_2 = \frac{(\sigma_{AU}^2 m_{HO} - \sigma_{HO}^2 m_{AU})}{\sigma_{HO}^2\sigma_{AU}^2}; \quad l_3 = \frac{(\sigma_{HO}^2 m_{AU}^2 - \sigma_{AU}^2 m_{HO}^2)}{2\sigma_{HO}^2\sigma_{AU}^2}, \quad (8)$$

then inequalities (4)–(7) will be written in terms of the coefficients l_1, l_2, l_3 as follows:

$$\frac{\sigma_{AU}}{\sigma_{HO}} e^{l_1 S_1^2 + l_2 S_1 + l_3} \geq 1; \quad (9)$$

$$\frac{\sigma_{AU}}{\sigma_{HO}} e^{l_1 S_2^2 + l_2 S_2 + l_3} \geq 1; \quad (10)$$

$$\frac{\sigma_{AU}}{\sigma_{HO}} e^{l_1 S_3^2 + l_2 S_3 + l_3} \geq 1; \quad (11)$$

$$\frac{\sigma_{AU}}{\sigma_{HO}} e^{l_1 S_4^2 + l_2 S_4 + l_3} \geq 1. \quad (12)$$

After logarithmizing on the basis of *e*, inequalities (9)–(12) are written as follows:

$$l_1 S_1^2 + l_2 S_1 + l_3 \geq ln \frac{\sigma_{HO}}{\sigma_{AU}}; \quad (13)$$

$$l_1 S_2^2 + l_2 S_2 + l_3 \geq ln \frac{\sigma_{HO}}{\sigma_{AU}}; \quad (14)$$

$$l_1 S_1^2 + l_2 S_1 + l_3 \geq ln \frac{\sigma_{HO}}{\sigma_{AU}}; \quad (15)$$

$$l_1 S_4^2 + l_2 S_4 + l_3 \geq ln \frac{\sigma_{HO}}{\sigma_{AU}}. \quad (16)$$

Solution of the obtained inequalities (13)–(16) with respect to the Stokes parameters S_1, S_2, S_3, S_4 of echo signals of a partially polarized wave of a complex object allows to obtain their criterion values $S_{1kr}, S_{2kr}, S_{3kr}, S_{4kr}$. Then, for all the Stokes parameters measured by SRPC $S_{1msr}, S_{2msr}, S_{3msr}, S_{4msr}$ their values will be greater than or equal to their criterion values, i.e.:

$$S_{1msr} \geq S_{1kr},\ S_{2msr} \geq S_{2kr},\ S_{3msr} \geq S_{3kr},\ S_{4msr} \geq S_{4kr}$$

and inequalities (13)–(16) will be valid. The operator of the SRPC shall decide on the presence on the indicator or display of the ship's computer of the echo signal only of the navigation object located at a given distance from the SRPC.

If the conditions of the above inequalities are not met, a decision is made on the presence of an atmospheric formation on the indicator of the SRPC or the display of the ship's computer, i.e.

$$S_{1msr} < S_{1kr}\,,\ S_{2msr} < S_{2kr}\,,\ S_{3msr} < S_{3kr}\,,\ S_{4msr} < S_{4kr}\,.$$

The basis for the use of the basic concepts of mathematical statistics and probability theory is the randomness of echo signals of Stokes parameters in the process of radar observation of navigation objects located in the zone of atmospheric formations by SRPC. The use of the maximum likelihood algorithm in solving the problem of polarization selection of navigation objects makes it possible to assign an echo signal to the object for which the likelihood function is greater.

The polarization selection of navigation objects using the maximum likelihood rule uses a smaller amount of a priori radar information and therefore the application of this rule is practically justified. When studying the values of the Stokes parameters of echo-signals for a navigation object and an atmospheric formation, their probability density distributions are close to normal, and the set of random values of the Stokes parameters of echo-signals of a navigation object and an atmospheric formation is considered as a random process of a complex object.

The values of the Stokes parameters of the navigation object and the atmospheric formation at discrete points in space and time were obtained for a certain period of time based on the results of radar measurements of the SRPC in the Zaporizhzhia region (Ukraine), taking into account the intensity of random precipitation and taking into account the radar information obtained in parallel with the MRL-5 meteorological radar. According to the obtained radar measurements of the SRPC, the echo signals of the first Stokes parameter of the navigation object and the atmospheric formation for a certain intensity of precipitation (in this case $I = 12$ mm/hour), statistical processing of the results of measuring the first Stokes parameter S_{1HO} and S_{1AU}, which are presented in Table 1 and Table 2, respectively.

Table 1. Results of radar observations of the SRPC echo-signal of a navigation object located in the zone of atmospheric formation and parameters of their statistical processing

Grades S_{1HO}	f	$P = f / N$	S_c	d	fd	d^2	fd^2
0.00 – 0.49	4	0.040	0.245	- 0.40	- 1.60	0.16	0.64
0.50 – 0.99	9	0.091	0.745	- 0.30	- 2.70	0.09	0.81
1.00 – 1.49	10	0.101	1.245	- 0.20	- 2.00	0.04	0.40
1.50 – 1.99	15	0.152	1.745	- 0.10	- 1.50	0.01	0.15
2.00 – 2.49	21	0.212	2.245	0.00	0.00	0.00	0.00
2.50 – 2.99	13	0.131	2.745	0.10	1.30	0.01	0.13
3.00 – 4.49	10	0.101	3.245	0.20	2.00	0.04	0.40
3.50 – 3.99	9	0.091	3.745	0.30	2.70	0.09	0.81
4.00 – 4.49	5	0.051	4.245	0.40	2.00	0.16	0.80
4.50 – 4.99	3	0.030	4.745	0.50	1.50	0.25	0.75
$\sum f = N$	**99**	**1.000**			**∑ 1.70**		**∑ 4.90**

Table 2. Results of radar observations of the SRPC echo-signal of atmospheric formation and parameters of their statistical processing

Grades S_{1AU}	*f*	$P = f / N$	$\overline{S}_1$	*d*	*fd*	d^2	fd^2
0.00 – 0.49	3	0.033	0.245	- 0.30	- 0.90	0.09	0.27
0.50 – 0.99	2	0.022	0.745	- 0.20	- 0.40	0.04	0.08
1.00 – 1.49	19	0.209	1.245	- 0.10	- 1.90	0.01	0.19
1.50 – 1.99	35	0.385	1.745	0.00	0.00	0.00	0.00
2.00 – 2.49	20	0.220	2.245	0.10	2.00	0.01	0.20
2.50 – 2.99	6	0.066	2.745	0.20	1.20	0.04	0.24
3.00 – 4.49	4	0.044	3.245	0.30	1.20	0.09	0.36
3.50 – 3.99	2	0.023	3.745	0.40	0.80	0.16	0.32
$\sum f=N$	**91**	**1.000**			$\sum$ **2.00**		$\sum$ **1.66**

Statistical processing of the results of radar observations of the navigation object and the atmospheric formation was carried out using statistical methods. In Tables 1 and 2, for each gradation of Stokes parameters S_{1HO} и S_{1AU} indicates the frequency f (number of cases). Sum of frequencies $\sum f$ of all grades of Stokes parameters is equal to the total number of observations *N*. Relationship $P = f / N$ is the probability of occurrence of a given gradation. The average value S_1 for each gradation is calculated using the following formula:

$$\overline{S}_1 = A + i\frac{\sum fd}{N}, \tag{17}$$

where *A* — the middle of the gradation with the largest amount of data S_1, that is, for a navigation object $A = 2.245$, and for atmospheric formation $A = 1.745$; *i* — the size of the gradation (for our case $i = 5$); $d = \frac{S_c - A}{i}$ — a positive or negative number indicating the number of the gradation.

The mathematical expectation for a navigation object and an atmospheric formation is determined using the following relationship:

$$\overline{S}_{1HO(AU)} = m_{S_{iHH(AU)}} = A + i\frac{\sum fd}{N}. \tag{18}$$

The mean square deviation determines the degree of variability of the random first Stokes parameter for the navigation object and the atmospheric formation, which is determined by the formula:

$$\sigma = i\sqrt{\frac{\sum fd^2}{N} - \left(\frac{\sum fd}{N}\right)^2}. \tag{19}$$

The variance, as the square of the standard deviation, is determined by the following formula:

$$\sigma^2 = \sigma^2\frac{N}{N-1}. \tag{20}$$

Based on the results of Tables 1 and 2 and the above formulas, we calculated the relevant statistical characteristics, i.e.:

$$m_{S_{1HO}} = 3.1; \quad \sigma_{S_{1HO}} = 1.1; \quad \sigma^2_{S_{1HO}} = 1.21.$$

$$m_{S_{1AU}} = 1.85; \quad \sigma_{S_{1AU}} = 0.66; \quad \sigma^2_{S_{1AU}} = 0.44.$$

Using the statistical parameters of the echo signals of the navigation object and the atmospheric formation, we calculated the coefficients l_1, l_2, l_3, which have the following values: $l_1 = 0.72$, $l_2 = -0.88$, $l_3 = -0.44$. After substituting them into inequality (9), we obtain:

$$0.72 S_1^2 - 0.88 S_1 - 0.55 > 0. \tag{21}$$

Solving inequality (21), we obtain two criterion values of the first Stokes parameter $S_{1kr(1)} > 1.68$ and $S_{1kr(2)} < -0.46$. Criterion value of the first Stokes parameter $S_{1kr(2)} < -0.46$ is rejected for physical reasons, since the probability of its occurrence for radar detection of the SRPC navigation object is zero, according to radar observations of a complex object. Therefore, the value of the first Stokes parameter $S_{1kr(1)} = 1.68$ will satisfy the solution of the problem of polarization selection of a navigation object located in the zone of atmospheric formation (precipitation of a certain intensity) and, when radar measurements of the echo signals of the first Stokes parameter are performed, will meet the following conditions $S_{1kr(1)} \geq 1.68$. That is, the task of polarization selection of the navigation object is solved. which is located in the zone of atmospheric formation (precipitation intensity of 12 mm/h). In this case, only the echo signal of the navigation object will be present on the SRPC indicator or on the computer display.

The polarization selection of navigation objects using the maximum likelihood rule (1) uses a smaller amount of a priori radar information and therefore the application of this rule is practically justified. To verify the fulfillment of condition (1), we solve equation (3) using the obtained statistical parameters.

For a navigation object: $m_{S_{1HO}} = 3.1$; $\sigma_{S_{1HO}} = 1.1$; $\sigma^2_{S_{1HO}} = 1.21$ 4; $S_{1HO} = 2.2$.

$$W(S_1 / HO) = \frac{1}{\sqrt{2\pi}\sigma_{HO}} e^{-\frac{(S_1 - m_{HO})^2}{2\sigma^2_{HO}}} = \frac{1}{2.5 \cdot 1.1} e^{-\frac{(2.2-3.1)^2}{2 \cdot 1.2}} = 0.36 \cdot 2.6 = 0.95.$$

For atmospheric formation: $m_{S_{1AU}} = 1.85$; $\sigma_{S_{1AU}} = 0.66$; $\sigma^2_{S_{1AU}} = 0.44$; $S_{1AU} = 1.75$.

$$W(S_1 / AU) = \frac{1}{\sqrt{2\pi}\sigma_{AU}} e^{-\frac{(S_1 - m_{AU})^2}{2\sigma^2_{AU}}} = \frac{1}{2.5 \cdot 0.66} e^{-\frac{(1.75-1.85)^2}{2 \cdot 0.44}} = 0.61 \cdot 1.1 = 0.67.$$

$$\frac{W(S_1 / HO)}{W(S_1 / AU)} = \frac{0.95}{0.67} = 1.4.$$

As a result of solving equation (3) using the first Stokes parameter as a predictor, the maximum likelihood rule (1) is fulfilled.

Thus the method proposed for polarized selection of navigation objects in challenging atmospheric conditions through shipboard radar polarization complexes (SRPC) involves a sophisticated approach. Leveraging the statistical properties of Stokes parameters from partially polarized electromagnetic waves derived from lunar signals of complex objects, the technique integrates a priori information to enhance radar observation system capabilities.

A pivotal aspect is the utilization of an omnipolarized antenna with controlled polarization, emphasizing the optimization of SRPC's energy capabilities by representing polarization through real energy Stokes parameters. The analysis of echo signals involves the simultaneous recording of all four Stokes parameters, enabling the polarization selection of navigation objects amidst atmospheric formations.

The application of the maximum likelihood rule is highlighted as a key component, demonstrating its practical justification due to its efficiency, particularly when a limited amount of a priori radar information is available. The derivation of criterion values for Stokes parameters is integral to the process, contributing to informed decision-making.

Radar measurements, considering precipitation intensity and utilizing data from a meteorological radar, provide a real-world context for the study. The statistical processing of radar observations for navigation objects and atmospheric formations involves the calculation of coefficients and verification of statistical parameters.

Accurate identification and tracking of navigation objects even in challenging atmospheric conditions provides ship operators with critical information to make informed decisions during maneuvers. This not only helps avoid collisions, but also enhances the safety of maritime activities. The integration of advanced polarimetric techniques is in line with the broader goal of improving navigation safety in a variety of environmental conditions.

CONCLUSIONS

The presented study outlines a systematic and data-driven methodology for polarimetric extraction of navigational objects in complex atmospheric conditions using shipboard radar polarization systems (SRPC). Using statistical properties of the Stokes parameters of partially polarized electromagnetic waves derived from lunar signals of complex objects, this approach integrates a priori information to improve the performance of radar surveillance systems.

The use of an omnipolarized antenna with controlled polarization is a critical element that emphasizes the optimization of SRPC energy capabilities by representing polarization through real Stokes energy parameters. The analysis of the echo signals includes simultaneous registration of all four Stokes parameters, enabling polarization selection of navigation objects in complex atmospheric formations.

The key point is the application of the maximum likelihood rule, which demonstrates its practical justification due to its effectiveness, especially in the conditions of limited amount of a priori radar information. The derivation of criterion values for the Stokes parameters is an integral part of the process, allowing informed decisions to be made in the context of polarization selection. The methodology offers a comprehensive and rigorous approach to polarization selection problems, demonstrating the integration of statistical analysis, radar measurements, and practical considerations. The results contribute to the understanding of polarimetric selection methods in navigation systems and may find applications in improving the performance of ship radar systems in various atmospheric conditions.

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МЕТОД ПОЛЯРИЗАЦІЙНОЇ СЕЛЕКЦІЇ НАВІГАЦІЙНИХ ОБ'ЄКТІВ У СКЛАДНИХ МЕТЕОРОЛОГІЧНИХ УМОВАХ З ВИКОРИСТАННЯМ СТАТИСТИЧНИХ ВЛАСТИВОСТЕЙ РАДІОСИГНАЛІВ / Д.В. Корбан, О.М. Мельник, С.В. Курдюк, О.А. Онищенко, В.В. Очеретна, О.В. Щербина, О.В. Котенко

Анотація. Присвячено дослідженню та застосуванню поляризаційної селекції для навігаційних об'єктів у складних атмосферних умовах. Основний акцент зроблено на використанні статистичних властивостей поляризаційних параметрів частково поляризованих ехо-сигналів. Детально розглянуто статистичні властивості поляризаційних параметрів частково поляризованих ехо-сигналів, які можуть бути використані для підвищення точності суднових радіолокаційних систем. Дослідження ґрунтується на аналізі експериментальних даних, зібраних у різних атмосферних умовах. Отримані результати свідчать про ефективність поляризаційної селекції для підвищення стійкості та точності навігаційних радіолокаційних систем у різних атмосферних умовах. Використання статистичних методів дозволяє радіолокаційній системі адаптуватися до мінливих умов, забезпечуючи надійність у різних сценаріях. Поляризаційна селекція на основі статистичних властивостей поляризаційних параметрів є перспективним методом покращення навігації в умовах підвищеної атмосферної вологості, туману та інших складних атмосферних умов і може бути використана у розробленні сучасних систем навігації.

Ключові слова: безпека судноплавства, атмосферні умови, статистичні властивості, часткова поляризація, ехо-сигнали, радіолокаційні системи, навігаційне обладнання, ресурси навігаційного містка, морський транспорт, радіолокація, керованість і маневрування суден.