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IMPLEMENTING THE COHERENCE MATRIX OF THE PARTIALLY POLARIZED WAVE TO ENHANCE EFFICIENCY OF RADAR OBSERVATION OF THE OBJECTS

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ВИКОРИСТАННЯ МАТРИЦІ КОГЕРЕНТНОСТІ ЧАСТКОВО ПОЛЯРИЗОВАНОЇ ХВИЛІ ДЛЯ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ РАДІОЛОКАЦІЙНОГО СПОСТЕРЕЖЕННЯ ОБ'ЄКТІВ

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ИСПОЛЬЗОВАНИЕ МАТРИЦЫ КОГЕРЕНТНОСТИ ЧАСТИЧНО ПОЛЯРИЗОВАННОЙ ВОЛНЫ ДЛЯ ПОВЫШЕНИЯ ЭФФЕКТИВНОСТИ РАДИОЛОКАЦИОННОГО НАБЛЮДЕНИЯ ОБЪЕКТОВ

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Abstract. *This article substantiates the possibility of radar observation of objects in the presence of atmospheric background. In the presence of an interfering background the radar observation of objects is based on the separation of the object's echo signal from the general echo signal (object + background) in accordance with its polarization difference. Therefore, the coherence matrix of a partially polarized wave is used, which allows to establish the structure of its fluctuating component. Application of such coherence matrix is shown to describe the properties of polarized and non-polarized fields. The coherence matrix combines the polarized and fluctuating components and is the coherence matrix of the total partially polarized wave reflected from the observed objects by radar and the atmospheric background. The elements of the coherence matrix are the actual Stokes parameters, which are the outcome values of the radar polarimeter. The diagonal elements of the coherence matrix are the intensities of the orthogonally polarized components of an electromagnetic wave, and not the diagonal elements determine their mutual correlation. The electromagnetic wave reflected from the navigation object and the atmospheric background is partially polarized and its total intensity is equal to the sum of the intensities of the stable and fluctuating components. The elements of the fluctuating component of the coherence matrix reflect the polarization structure of the partially polarized wave and represent the variances of the random Stokes polarization parameters and their statistical relationship. For an unpolarized wave, the coherence matrix is diagonal in any polarization basis. The total coherence matrix provides information on the polarization of a partially polarized wave reflected from the navigation object and the atmospheric background. A necessary condition for remote radar observation of navigation objects located in the atmospheric background zone is the separation of the echo signal into the echo signal of the navigation object and the echo signal of the atmospheric formation, which are statistically independent. According to the Stokes theorem, the echo signal of a partially polarized wave is decomposed into polarized and unpolarized components. A fully polarized component of a total partially polarized wave has only one type of polarization — linear, circular, or elliptical. The unpolarized component does not have any predominant polarization. The echo signal of the total partially polarized wave is considered as a result of the addition of the intensities of two independent fully polarized components. The polarization of the first component corresponds to the echo signal of the navigation object, and the polarization of the second component corresponds to the echo signal of the atmospheric formation.*

Keywords: *coherence matrix, radar observation of objects, polarization parameters of an electromagnetic wave, atmospheric background, polarization difference of the object's echo signal and atmospheric background.*

Анотація. *У статті обґрунтована можливість радіолокаційного спостереження об'єктів за наявності атмосферного фону. Радіолокаційне спостереження об'єктів за наявності заважального фону основане на виділенні луно-сигналу об'єкта з сумарного луно-сигналу (об'єкт + фон) за їх поляризаційною відмінністю. При цьому використана матриця когерентності частково поляризованої хвилі, що дозволяє установити структуру її флюктуючої компоненти. Показано застосування матриці когерентності для опису властивостей поляризаційного і не поляризаційного полів. Матриця когерентності об'єднує поляризовану і флюктуючу компоненти, і є матрицею когерентності сумарної частково поляризованої хвилі, відбитої від спостережуваного РЛС об'єкта і атмосферного фону. Елементами матриці когерентності є дійсні параметри Стокса, які є вихідними величинами радіолокаційного поляриметра. Діагональні елементи матриці когерентності є інтенсивностями ортогонально поляризованих компонент електромагнітної хвилі, а не діагональні елементи визначають їх взаємну кореляцію. Відбита від навігаційного об'єкта і атмосферного фону електромагнітна хвиля є частково поляризованою і її повна інтенсивність дорівнює сумі інтенсивностей стабільної і флюктуючої компонент. Елементи флюктуючої компоненти матриці когерентності відображають поляризаційну структуру частково поляризованої хвилі і являють дисперсії випадкових поляризаційних параметрів Стокса та їх статистичний зв'язок. Для неполяризованої хвилі матриця когерентності є діагональною в будь-якому поляризаційному базисі. Сумарна матриця когерентності дозволяє отримати інформацію про поляризацію частково поляризованої хвилі, відбитої від навігаційного об'єкта і атмосферного фону. Необхідною умовою дистанційного радіолокаційного спостереження навігаційних об'єктів, що знаходяться в зоні атмосферного фону, є поділ луно-сигналу на луно-сигнал навігаційного об'єкта і луно-сигнал атмосферного утворення, які є статистично незалежними. За теоремою Стокса проводиться розкладання луно-сигналу частково поляризованої хвилі на поляризовану і неполяризовану компоненти. Повністю поляризована компонента сумарної частково поляризованої хвилі володіє тільки одним з видів поляризації – лінійною, круговою або еліптичною. Неполяризована компонента не володіє будь-якою переважною поляризацією. Відлуння-сигнал сумарної частково поляризованої хвилі розглядається як результат складання інтенсивностей двох незалежних повністю поляризованих компонент. Поляризація першої компоненти відповідає луно-сигналу навігаційного об'єкта, а поляризація другої компоненти відповідає луно-сигналу атмосферного утворення.*

Ключові слова: *матриця когерентності, радіолокаційне спостереження об'єктів, поляризаційні параметри електромагнітної хвилі, атмосферний фон, поляризаційна відмінність луно-сигналу об'єкта і атмосферного фону.*

Аннотация. *В статье обоснована возможность радиолокационного наблюдения объектов при наличии атмосферного фона. Радиолокационное наблюдение объектов при наличии мешающего фона основано на выделении эхо-сигнала объекта из суммарного эхо-сигнала (объект+фон) по их поляризационному различию. При этом использована матрица когерентности частично поляризованной волны, позволившая установить структуру ее флуктуирующей компоненты. Показано применение матрицы когерентности для описания свойств поляризованного и неполяризованного полей. Матрица когерентности объединяет поляризованную и флуктуирующую компоненты и является матрицей когерентности суммарной частично поляризованной волны, отраженной от наблюдаемого РЛС объекта и атмосферного фона. Элементами матрицы когерентности являются действительные параметры Стокса, которые являются выходными величинами радиолокационного поляриметра. Диагональные элементы матрицы когерентности являются интенсивностями ортогонально поляризованных компонент электромагнитной волны, а не диагональные элементы определяют их взаимную корреляцию. Отраженная от навигационного объекта и атмосферного фона электромагнитная волна является частично поляризованной и ее полная интенсивность равна сумме интенсивностей стабильной и флуктуирующей компонент. Элементы флуктуирующей компоненты матрицы когерентности отражают поляризационную структуру частично поляризованной волны и представляют дисперсии случайных поляризационных параметров Стокса и их статистическую связь. Для неполяризованной волны матрица когерентности является диагональной в любом поляризационном базисе. Суммарная матрица когерентности позволяет получить информацию о поляризации частично поляризованной волны, отраженной от навигационного объекта и атмосферного фона. Необходимым условием дистанционного радиолокационного наблюдения навигационных объектов, находящихся в зоне атмосферного фона, является разделение эхо-сигнала на эхо-сигнал навигационного объекта и эхо-сигнал атмосферного образования, которые являются статистически независимыми. По теореме Стокса производится разложение эхо-сигнала частично поляризованной волны на поляризованную и неполяризованную компоненты. Полностью поляризованная компонента суммарной частично поляризованной волны обладает только одним из видов поляризации – линейной, круговой или эллиптической. Неполяризованная компонента не обладает какой-либо преимущественной поляризацией. Эхо-сигнал суммарной частично поляризованной волны рассматривается как результат сложения интенсивностей двух независимых полностью поляризованных компонент. Поляризация первой компоненты соответствует эхо-сигналу навигационного объекта, а поляризация второй компоненты соответствует эхо-сигналу атмосферного образования.*

Ключевые слова: *матрица когерентности, радиолокационное наблюдение объектов, поляризационные параметры электромагнитной волны, атмосферный фон, поляризационное различие эхо-сигнала объекта и атмосферного фона.*

PROBLEM STATEMENT IN A GENERAL VIEW AND HIGHLIGHTING COMMON QUESTIONS

Radar observation of objects on the ship’s route has a number of features that are associated with an influence of the atmosphere on the parameters of the reflected signals. The interfering background as such is an atmosphere formed echo signal, which masks the observed object’s signal. During the radar observation of objects, the coherence matrix develops its own characteristics which define the polarization transformations of an electromagnetic wave during its spreading in the atmosphere. Observed navigation objects by ship’s radar are complex radar targets which are characterized by constantly changing coordinates. These coordinates must be remotely measured with the precise accuracy under adverse environmental conditions. Currently, almost all the obvious ways to reduce the environmental impact on the radar observation of navigation objects by the ship’s radar have been already achieved [1, 2, 3]. Therefore, Radar polarimetry methods which have received a powerful incentive for their implementation are on the agenda today. However, a lot of methods of polarization analysis in the marine radar observations of an electromagnetic wave have not been implemented as yet. Due to an influence of atmospheric noise on radar observation of navigation objects, it became necessary to search for various methods of polarization selection of the echo signals [4, 5], the development of which is currently ongoing.

Radar echo emission efficiency of the navigation object from the echo signal of atmospheric interference is still insufficient which leads to a significant decrease in the visibility of the observed object by ship’s radar.

The aim of this article is to justify the use of a coherence matrix of a partially polarized wave to increase the efficiency of radar observation of objects.

THE PRESENTATION OF THE MAIN MATERIAL AND THE JUSTIFICATION OF SCIENTIFIC RESULTS.

Conditions of the atmospheric environment affect the work of the ship's radar when observing a navigation object. Moreover, the radio vision of the navigation object and the condition of the atmospheric environment are functionally related. When analyzing an impact of the atmospheric environment on the operation of ship’s radar, it is necessary to consider the disturbance created by the environment and determine what is known from what is unknown by means of differentiating, which is parameterized by certain characteristics. While it is almost impossible to influence the dynamics of atmospheric formation on the ship’s route from the outside, the goal of successful operation of the ship’s radar is to choose a strategy by which the incoming impact determines definitely the outgoing signal. This strategy is determined using the coefficients of the matrix model, the dimension of which allows matching the incoming and outgoing signals in one equation. The matrix model establishes the interaction of the navigation object with the atmospheric environment. An electromagnetic, partially polarized wave, reflected from a navigation object and an atmospheric formation, can be represented as a combination of a fully polarized signal and an echo signal of a partially polarized interference, which has no deterministic component.

When analyzing and synthesizing a polarization state of an echo signal of a partially polarized electromagnetic wave reflected from a navigation object and an atmospheric formation, it is necessary to decompose (receive) the echo signal separately into polarization channels defined by orts l_1, l_2 . As the partially polarized wave reflected from the navigation and atmospheric objects consists of fully polarized and non-polarized waves, it is a superposition of two elliptically polarized waves that are incoherent with each other in general form.

During the radar observation of navigation objects, the electromagnetic wave emitted by the antenna, causes induced oscillations of broad and bound charges on the surface of the object, regardless of its nature. If the navigation object is in the zone of atmospheric formation (rain, cloud etc.), the incident wave also causes induced oscillations in the elementary reflectors, which are distributed within the resolution element of the atmospheric formation. As a result of induced oscillations, a secondary field is created inside the atmospheric formation and on the surface of the navigation object that represents the reflected incoming signal to the ship's radar antenna.

The electromagnetic wave which is reflected from the navigation object depends on its shape, size and electrical quality but an electromagnetic wave which is reflected from elementary reflectors of atmospheric formation appears as a result of signal interference of reflectors within the resolution element. The reflected signal is also dependent on the length of the radiated antenna of the ship's radar wave and its polarization.

The navigation object is an object of complex configuration, consisting of a number of the rigidly interconnected basic reflective elements. The atmospheric formation in which the navigation object is located is a combination of individual reflectors in a certain area of space (volumetric distribution). In the process of radar observation, the position of the object changes relatively to the ship's radar. Atmospheric formation is a volume-distributed object, consisting of a large number of arbitrarily located elementary reflectors (particles of precipitation). Part of the navigation object are bright dots which have a stable reflected signal with amplitude which exceeds the sum of all signal amplitudes reflected from all other elements.

Since the amplitudes and phases of the echoes of other elements of the navigation object, as well as reflective particles of atmospheric formation, experience random changes during relative movements of the ship's radar, navigation object and atmospheric formation, resulting fluctuations of the resulting echo signal. Then the resulting echo signal can be represented in a known form.

$$U_{res} = U_{br.p} \cos \omega t + U_{\Sigma_{el.ref}} \cos \left(\omega t - \varphi_{\Sigma_{el.ref}} \right), \tag{1}$$

where $U_{br.p}$ is the amplitude of the bright dot signal; $U_{\Sigma_{el.ref}}$ and $\varphi_{\Sigma_{el.ref}}$ – the amplitude and phase of the resulting signal from the elementary reflectors.

The amplitude of the resulting echo signal of elementary reflectors consists of the sum of two orthogonal components (cosine $U_{\Sigma_{\cos 1}}$ and sinusoidal $U_{\Sigma_{\sin 2}}$):

$$U_{\Sigma_{el.ref}} = \sqrt{U^2_{\Sigma_{\cos 1}} + U^2_{\Sigma_{\sin 2}}} . \tag{2}$$

The echo component $U_{\Sigma_{\cos 1}}$ is summed with the echo signal of the bright dot $U_{br.p}$ of the navigation object and, taking into account their phase coincidence, form the resulting fully polarized coherent echo signal with amplitude U_1:

$$U_1 = U_{br.p} + U_{\Sigma_{\cos 1}} . \tag{3}$$

The amplitude of the sinusoidal component of the echo signal $U_{\Sigma_{\sin 2}}$ forms the fluctuating echo signal U_2, orthogonal to the echo signal U_1:

$$U_2 = U_{\Sigma_{\sin 2}} .$$

These two orthogonal vectors U_1 and U_2 of the echo signal are statistically independent on each other, since the change in the amplitude of one does not affect the change in the amplitude of the other.

The amplitude of the resulting echo signal is determined from the condition:

$$U_{res} = \sqrt{U_2^1 + U_2^2} \tag{4}$$

It's necessary to separate the total echo signal from the echo signal of the navigation object located in the zone of the atmospheric formation, taking into account that the deterministic component belongs to the navigation object, and the fluctuating component belongs to the atmospheric formation.

And although the navigation object is a complex object, however, its echoes during the time of the radar observation give almost non-fluctuating reflection. Atmospheric formation is a fluctuating object (interfering background), which impedes the radar observation of the navigation object.

To solve this problem, we will use the coherence matrix of a partially polarized wave reflected from a navigation object and an atmospheric formation consisting of a set of Stoke's parameters. The Stoke's parameters allow us to determine the polarization of the wave at the antenna input on ship's radar only on the measured intensities. For partially polarized waves consisting of fluctuation and monochromatic components, the existing methods used in network of radar and radar systems do not allow separating the energy parameters of the fluctuation and monochromatic components of the echo signal.

Taking into account the fluctuating and monochromatic components in an echo-signal of a partially polarized wave for radar observation of navigational objects, first-order moments can be used, in which the Stokes parameters sufficiently characterize the differential law of probability distribution of these real parameters $W_n(S_1, S_2, S_3, S_4)$, which exists and is integrated in the whole space of possible values of $S_k\left(K = 1, 2, 3, 4\right)$.

The real Stoke's parameters, which include the amplitudes of the orthogonal components of a partially polarized wave, will correspond to the first-order moments (mathematical expectations) [6]

$$\begin{aligned} M\left[S_{\mathrm{k}}\right] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\Delta} W_n\left(S_1, S_2, S_3, S_4\right) S_k dS_1 dS_2 dS_3 dS_4 + \\ + \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} W_n\left(S_1, S_2, S_3, S_4\right) S_{\mathrm{k+1}} dS_1, dS_2, dS_3, dS_4 \;\cdot \end{aligned} \tag{5}$$

Since the phase fronts of the echo signals of the navigation object and the atmospheric formation coincide and spread in the same direction, at a selected space point, the ship's radar observes an echo signal of a total partially polarized wave with properties determined by the nature of the folding waves.

Imagine the polarization of an arbitrary electromagnetic wave in an arbitrary basis by the well-known Stoke's parameter vector $S(t)$ in the form of a column matrix which will allow to form the coherence matrix $R_e(t)$ [7]:

$$S(t) = \begin{bmatrix} S_1(t) \\ S_2(t) \\ S_3(t) \\ S_4(t) \end{bmatrix}, \tag{6}$$

where $S_1(t)$, $S_2(t)$, $S_3(t)$, $S_4(t)$ – the Stoke's parameters in a linear basis, which are written in the form:

$$\begin{gathered} S_1(t) = \left\langle E_x^2(t) + E_y^2(t) \right\rangle \\ S_2(t) = \left\langle E_x^2(t) - E_y^2(t) \right\rangle \\ S_3(t) = 2\left\langle E_x(t) E_y(t) \cos \Phi_{xy}(t) \right\rangle \\ S_4(t) = 2\left\langle E_x(t) E_y(t) \sin \Phi_{xy}(t) \right\rangle. \end{gathered} \tag{7}$$

The sign $\langle\ \rangle$ is the time averaging of the Cartesian components of the transverse electric field of the wave.

For the considered arbitrary electric field of a wave defined in some basis by the Stoke's vector (6), we form an auxiliary matrix C, the elements of the first column of which are the Stoke's parameters and the elements of the second are zeros

$$S(t)=\begin{bmatrix} S_1(t) & 0 \\ S_2(t) & 0 \\ S_3(t) & 0 \\ S_4(t) & 0 \end{bmatrix}. \tag{8}$$

Imagine the Hermitian-conjugate matrix in the form:

$$C^{+}_{(t)}=\tilde{C}^{*}_{(t)}=\begin{bmatrix} S_1(t)* & S_2(t)* & S_3(t)* & S_4(t)* \\ 0 & 0 & 0 & 0 \end{bmatrix}. \tag{9}$$

The product of the matrices $C(t)\cdot C^{+}(t)$ will give the coherence matrix of an arbitrary electromagnetic wave

$$R_e(t)=C(t)\cdot C^{+}(t)=\begin{bmatrix} S_1(t)S_1(t)* & S_1(t)S_2(t)* & S_1(t)S_3(t)* & S_1(t)S_4(t)* \\ S_2(t)S_1(t)* & S_2(t)S_2(t)* & S_2(t)S_3(t)* & S_2(t)S_4(t)* \\ S_3(t)S_1(t)* & S_3(t)S_2(t)* & S_3(t)S_3(t)* & S_3(t)S_4(t)* \\ S_4(t)S_1(t)* & S_4(t)S_2(t)* & S_4(t)S_3(t)* & S_4(t)S_4(t)* \end{bmatrix}. \tag{10}$$

The diagonal elements of the matrix (10) are the intensities of the orthogonally polarized components of the wave, represented by the actual energy parameters of Stoke's. The total intensity of the wave is equal to their sum:

$$I=S_1(t)S_1(t)*+S_2(t)S_2(t)*+S_3(t)S_3(t)*+S_4(t)S_4(t)*. \tag{11}$$

The off-diagonal elements of the matrix $R_e(t)$ determine their mutual correlation.

A partially polarized wave reflected from a navigation object and an atmospheric formation consists of the sum of two statistically independent components: stable and fluctuating. When analyzing an echo signal of a partially polarized wave, consider the coherence matrix of the stable component and the coherence matrix of the fluctuating component.

The coherence matrix of a stable component of an echo signal of a partially polarized wave is defined as the mathematical expectation of the product of the vector $S(t)$ represented by the elements of the column matrix of the stable component of the Stoke's parameters of the partially polarized wave $M[S(t)]$ and the vector $M[S^{\triangleright}(t)]$ Hermitian-conjugate vector $S(t)$, also represented by the Stoke's parameters:

$$R_{St}(t)=M[S(t)]\cdot M[S^{\triangleright}(t)]=$$

$$=\begin{bmatrix} M[S_{1St}(t)]M[S^{*}_{1St}(t)] & M[S_{1St}(t)]M[S^{*}_{2St}(t)] & M[S_{1St}(t)]M[S^{*}_{3St}(t)] & M[S_{1St}(t)]M[S^{*}_{4St}(t)] \\ M[S_{2St}(t)]M[S^{*}_{1St}(t)] & M[S_{2St}(t)]M[S^{*}_{2St}(t)] & M[S_{2St}(t)]M[S^{*}_{3St}(t)] & M[S_{2St}(t)]M[S^{*}_{4St}(t)] \\ M[S_{3St}(t)]M[S^{*}_{1St}(t)] & M[S_{3St}(t)]M[S^{*}_{2St}(t)] & M[S_{3St}(t)]M[S^{*}_{3St}(t)] & M[S_{3St}(t)]M[S^{*}_{4St}(t)] \\ M[S_{4St}(t)]M[S^{*}_{1St}(t)] & M[S_{4St}(t)]M[S^{*}_{4St}(t)] & M[S_{4St}(t)]M[S^{*}_{3St}(t)] & M[S_{4St}(t)]M[S^{*}_{4St}(t)] \end{bmatrix}=$$

$$=\begin{bmatrix} S_{11St}(t) & S_{12St}(t) & S_{13St}(t) & S_{14St}(t) \\ S_{21St}(t) & S_{22St}(t) & S_{23St}(t) & S_{24St}(t) \\ S_{31St}(t) & S_{32St}(t) & S_{33St}(t) & S_{34St}(t) \\ S_{41St}(t) & S_{42St}(t) & S_{43St}(t) & S_{44St}(t) \end{bmatrix}. \tag{12}$$

The vector $S_{St}(t)^{\triangleright}$ is Hermitian conjugate to the vector $S_{St}(t)$ and is a vector string written in the form:

$$M\left[S_{St}(t)\right]^{\triangleright}=M\left[S^*_{1St}(t)\right]\cdot M\left[S^*_{2St}(t)\right]\cdot M\left[S^*_{3St}(t)\right]\cdot M\left[S^*_{4St}(t)\right]. \tag{13}$$

The determinant Δ_{St} of the matrix (12) is written in the form

$$\Delta_{St}=S_{11St}(t)A_1+S_{12St}(t)B_1+S_{13St}(t)C_1+S_{14St}(t)D_1, \tag{14}$$

where A, B, C, D – algebraic additions to matrix elements $S_{11St}(t)$, $S_{12St}(t)$, $S_{13St}(t)$, $S_{14St}(t)$,

$$\left.\begin{matrix} A_1=\begin{bmatrix} S_{22St}(t) & S_{23St}(t) & S_{24St}(t) \\ S_{32St}(t) & S_{33St}(t) & S_{34St}(t) \\ S_{42St}(t) & S_{43St}(t) & S_{44St}(t) \end{bmatrix}, & B_1=\begin{bmatrix} S_{21St}(t) & S_{23St}(t) & S_{24St}(t) \\ S_{31St}(t) & S_{33St}(t) & S_{34St}(t) \\ S_{41St}(t) & S_{43St}(t) & S_{44St}(t) \end{bmatrix} \\ C_1=\begin{bmatrix} S_{21St}(t) & S_{22St}(t) & S_{24St}(t) \\ S_{31St}(t) & S_{32St}(t) & S_{34St}(t) \\ S_{41St}(t) & S_{42St}(t) & S_{44St}(t) \end{bmatrix}, & D_1=\begin{bmatrix} S_{21St}(t) & S_{22St}(t) & S_{23St}(t) \\ S_{31St}(t) & S_{32St}(t) & S_{33St}(t) \\ S_{41St}(t) & S_{42St}(t) & S_{43St}(t) \end{bmatrix} \end{matrix}\right\} \qquad 15)$$

Taking into account (15), equation (14) will take the value:

$$\Delta_{St}=S_{11St}(t)\cdot\begin{bmatrix} S_{22St}(t) & S_{23St}(t) & S_{24St}(t) \\ S_{32St}(t) & S_{33St}(t) & S_{34St}(t) \\ S_{42St}(t) & S_{43St}(t) & S_{44St}(t) \end{bmatrix}+S_{12St}(t)\cdot\begin{bmatrix} S_{21St}(t) & S_{23St}(t) & S_{24St}(t) \\ S_{31St}(t) & S_{33St}(t) & S_{34St}(t) \\ S_{41St}(t) & S_{43St}(t) & S_{44St}(t) \end{bmatrix}+$$

$$+S_{13St}(t)\cdot\begin{bmatrix} S_{21St}(t) & S_{22St}(t) & S_{24St}(t) \\ S_{31St}(t) & S_{32St}(t) & S_{34St}(t) \\ S_{41St}(t) & S_{42St}(t) & S_{44St}(t) \end{bmatrix}+S_{14St}(t)\cdot\begin{bmatrix} S_{21St}(t) & S_{22St}(t) & S_{23St}(t) \\ S_{31St}(t) & S_{32St}(t) & S_{33St}(t) \\ S_{41St}(t) & S_{42St}(t) & S_{43St}(t) \end{bmatrix}. \tag{16}$$

Analysis of formula (11) shows that the determinant of the matrix $R_{S\,St}(t)$ for a stable (monochromatic) polarization component is zero. The coherence matrix $R_{S\,fl}$ of the fluctuating component of a partially polarized wave is also the mathematical expectation of the product of vectors $S_{fl}(t)$ and $S_{fl}(t)^{\triangleright}$

$$R_{S\,fl}(t)=M\left[S_{fl}(t)S_{fl}(t)^{\triangleright}\right]=$$

$$=\begin{bmatrix} M\left[S_{1fl}(t)S^*_{1fl}(t)\right] & M\left[S_{1fl}(t)S^*_{2fl}(t)\right] & M\left[S_{1fl}(t)S^*_{3fl}(t)\right] & M\left[S_{1fl}(t)S^*_{4fl}(t)\right] \\ M\left[S_{2fl}(t)S^*_{1fl}(t)\right] & M\left[S_{2fl}(t)S^*_{2fl}(t)\right] & M\left[S_{2fl}(t)S^*_{3fl}(t)\right] & M\left[S_{2fl}(t)S^*_{4fl}(t)\right] \\ M\left[S_{3fl}(t)S^*_{1fl}(t)\right] & M\left[S_{3fl}(t)S^*_{2fl}(t)\right] & M\left[S_{3fl}(t)S^*_{3fl}(t)\right] & M\left[S_{3fl}(t)S^*_{4fl}(t)\right] \\ M\left[S_{4fl}(t)S^*_{1fl}(t)\right] & M\left[S_{4fl}(t)S^*_{2fl}(t)\right] & M\left[S_{4fl}(t)S^*_{3fl}(t)\right] & M\left[S_{4fl}(t)S^*_{4fl}(t)\right] \end{bmatrix}=$$

$$=\begin{bmatrix} S_{11fl}(t) & S_{12fl}(t) & S_{13fl}(t) & S_{14fl}(t) \\ S_{21fl}(t) & S_{22fl}(t) & S_{23fl}(t) & S_{24fl}(t) \\ S_{31fl}(t) & S_{32fl}(t) & S_{33fl}(t) & S_{34fl}(t) \\ S_{41fl}(t) & S_{42fl}(t) & S_{43fl}(t) & S_{44fl}(t) \end{bmatrix}. \tag{17}$$

The elements of the matrices $R_{S\,St}(t)$ and $R_{S\,fl}(t)$, which are the Stoke's parameters, have the dimension of intensities and the sum of the diagonal coefficients of the matrices is equal to the total intensity of the stable and fluctuating components of the partially polarized wave,

$$I_{St}=S_{11St}(t)+S_{22St}(t)+S_{33St}(t)+S_{44St}(t), \tag{18}$$

$$I_{fl}=S_{11\,fl}(t)+S_{22\,fl}(t)+S_{33\,fl}(t)+S_{44\,fl}(t). \tag{19}$$

The total intensity I of a partially polarized wave is equal to the sum of the intensities of the stable and fluctuating components, i.e.

$$I=I_{St}+I_{fl}=\left(S_{11St}(t)+S_{11\,fl}(t)\right)+\left(S_{22St}(t)+S_{22\,fl}(t)\right)+\left(S_{33St}(t)+S_{33\,fl}(t)\right)+\left(S_{44St}(t)+S_{44\,fl}(t)\right). \tag{20}$$

The elements of the fluctuating component of the matrix $R_{S\,fl}(t)$ reflect the polarization structure of the partially polarized wave and represent the dispersions of random polarization Stoke's parameters and their statistical relationship. Then the sum of the diagonal elements of the matrix is equal to the total intensity I of the fluctuations of the partially polarized wave and is written in the form:

$$I_{fl}=S_{11fl}(t)+S_{22fl}(t)+S_{33fl}(t)44_{11fl}(t)=\sigma_1^2+\sigma_2^2+\sigma_3^2+\sigma_4^2. \tag{21}$$

Matrix determinant $R_{S\,fl}(t)\geq 0$.

For a non-polarized wave, the coherence matrix $R_{e\,fl}(t)$ is diagonal in any polarization basis

$$R_{S\,n.p}(t)=\begin{bmatrix} S_{11} & 0 & 0 & 0 \\ 0 & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & 0 \\ 0 & 0 & 0 & S_{44} \end{bmatrix}=0{,}5\,I\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{22}$$

The coherence matrix $R_{S\,\Sigma}$ of the total partially polarized wave combines the matrices $R_{S\,St}(t)\multimap$ and $R_{S\,fl}(t)$, and is written in the form:

$$R_{S\,\Sigma}(t)=R_{S\,St}(t)+R_{S\,fl}(t)=$$

$$=\begin{bmatrix} S_{11St}(t) & S_{12St}(t) & S_{13St}(t) & S_{14St}(t) \\ S_{21St}(t) & S_{22St}(t) & S_{23St}(t) & S_{24St}(t) \\ S_{31St}(t) & S_{32St}(t) & S_{33St}(t) & S_{34St}(t) \\ S_{41St}(t) & S_{42St}(t) & S_{43St}(t) & S_{44St}(t) \end{bmatrix}+\begin{bmatrix} S_{11\,fl}(t) & S_{12\,fl}(t) & S_{13\,fl}(t) & S_{14\,fl}(t) \\ S_{21\,fl}(t) & S_{22\,fl}(t) & S_{23\,fl}(t) & S_{24\,fl}(t) \\ S_{31\,fl}(t) & S_{32\,fl}(t) & S_{33\,fl}(t) & S_{34\,fl}(t) \\ S_{41\,fl}(t) & S_{42\,fl}(t) & S_{43\,fl}(t) & S_{44\,fl}(t) \end{bmatrix}=$$

$$=\begin{bmatrix} S_{11\Sigma}(t) & S_{12\Sigma}(t) & S_{13\Sigma}(t) & S_{14\Sigma}(t) \\ S_{21\Sigma}(t) & S_{22\Sigma}(t) & S_{23\Sigma}(t) & S_{24\Sigma}(t) \\ S_{31\Sigma}(t) & S_{32\Sigma}(t) & S_{33\Sigma}(t) & S_{34\Sigma}(t) \\ S_{41\Sigma}(t) & S_{42\Sigma}(t) & S_{43\Sigma}(t) & S_{44\Sigma}(t) \end{bmatrix}, \tag{23}$$

where

$$S_{11\Sigma}=S_{11St}+S_{11\,fl}, \qquad S_{31\Sigma}=S_{31St}+S_{31\,fl},$$

$$S_{12\Sigma}=S_{12St}+S_{12\,fl}, \qquad S_{32\Sigma}=S_{32St}+S_{32\,fl},$$

$$S_{13\Sigma}=S_{13St}+S_{13\,fl}, \qquad S_{33\Sigma}=S_{33St}+S_{33\,fl},$$

$$S_{14\Sigma}=S_{14St}+S_{14\,fl}, \qquad S_{34\Sigma}=S_{34St}+S_{34\,fl},$$

$$S_{21\Sigma}=S_{21St}+S_{21\,fl}, \qquad S_{41\Sigma}=S_{41St}+S_{41\,fl},$$

$$S_{22\Sigma} = S_{22St} + S_{22fl}, \quad S_{42\Sigma} = S_{42St} + S_{42fl},$$

$$S_{23\Sigma} = S_{23St} + S_{23fl}, \quad S_{43\Sigma} = S_{43St} + S_{43fl},$$

$$S_{44\Sigma} = S_{44St} + S_{44fl}, \quad S_{44\Sigma} = S_{44St} + S_{44fl}.$$

The total coherence matrix $R_{S\Sigma}(t)$ makes it possible to obtain information about the polarization of a partially polarized wave reflected from a navigation object and an atmospheric formation since the elements of the matrix are the Stoke's energy parameters which are easily measured by ship's radar. The necessary condition for remote radar observation of a navigation object which is located in the zone of atmospheric formation is the separation of the echo signals into the echo signal of the navigation object and the echo signal of atmospheric formation, which are statistically independent. The polarization features of some individual electromagnetic waves, that are part of an echo signal of a total partially polarized wave are given by a set of Stoke's parameters and, in the absence of a statistical connection between individual waves, the polarization properties of a total partially polarized wave are described by the sum of the following parameters:

$$S_{l\Sigma} = \sum_{m=1}^{n} S_{lm}, \ (l = 0, 1, 2, 3). \tag{24}$$

The coherence matrix of a superposition of independent echoes of a partially polarized wave is the sum of the corresponding characteristics of its individual components, represented by the Stoke's parameters. Using the Stoke's theorem [6], one can decompose the echo signal of a partially polarized wave into polarized and non-polarized components which are also described by the coherence matrices of the polarized and non-polarized components.

Then the total coherence matrix of the echo of a partially polarized wave is written as follows:

$$R_{S\Sigma}(t) = R_{S\,St}(t) + R_{S\,fl}(t) = R_{S\,St}(t) + R_{S\,fl.p}(t) + R_{S\,fl.n.p}(t) =$$

$$= \begin{bmatrix} S_{11St}(t) & S_{12St}(t) & S_{13St}(t) & S_{14St}(t) \\ S_{21St}(t) & S_{22St}(t) & S_{23St}(t) & S_{24St}(t) \\ S_{31St}(t) & S_{32St}(t) & S_{33St}(t) & S_{34St}(t) \\ S_{41St}(t) & S_{42St}(t) & S_{43St}(t) & S_{44St}(t) \end{bmatrix} + \begin{bmatrix} S_{11fl}(t) & S_{12fl}(t) & S_{13fl}(t) & S_{14fl}(t) \\ S_{21fl}(t) & S_{22fl}(t) & S_{23fl}(t) & S_{24fl}(t) \\ S_{31fl}(t) & S_{32fl}(t) & S_{33fl}(t) & S_{34fl}(t) \\ S_{41fl}(t) & S_{42fl}(t) & S_{43fl}(t) & S_{44fl}(t) \end{bmatrix} =$$

$$= \begin{bmatrix} S_{11\,n.p} & 0 & 0 & 0 \\ 0 & S_{22\,n.p} & 0 & 0 \\ 0 & 0 & S_{33\,n.p} & 0 \\ 0 & 0 & 0 & S_{44\,n.p} \end{bmatrix}, \tag{25}$$

where

$$R_{S\,fl}(t) = R_{S\,fl.p}(t) + R_{S\,fl.n.p}(t).$$

The total intensity I_{tot} echo of a partially polarized wave of a navigation object and atmospheric formation is found as the sum of the diagonal elements of the matrices

$$R_{S\,St_p}(t), \ R_{S\,fl_p}(t), \ R_{S\,fl_{n.p}}(t),$$

i.e.

$$I_{tot} = I_p + I_{n.p} = S_{11\,St_p}(t) + S_{22\,St_p}(t) + S_{33\,St_p}(t) + S_{44\,St_p}(t) + S_{11\,fl_p}(t) + S_{22\,fl_p}(t) +$$

$$+ S_{33\,fl_p}(t) + S_{44\,fl_p}(t) + S_{11\,fl_{n.p}}(t) + S_{22\,fl_{n.p}}(t) + S_{33\,fl_{n.p}}(t) + S_{44\,fl_{n.p}}(t). \tag{26}$$

The intensity of the echo signal of a polarized component of a partially polarized wave is written as:

$$I_p = S_{11St_p}(t)+S_{22St_p}(t)+S_{33St_p}(t)+S_{44St_p}(t)+S_{11fl_p}(t)+S_{22fl_p}(t)+S_{33fl_p}(t)+S_{44fl_p}(t)= \\ = S_{1\Sigma}(t)+S_{2\Sigma}(t)+S_{3\Sigma}(t)+S_{4\Sigma}(t)\ ,$$

$$I_{n.p} = S_{11fl_{n.p}}(t)+S_{22fl_{n.p}}(t)+S_{33fl_{n.p}}(t)+S_{44fl_{n.p}}(t)=S_{1n.p}(t)+S_{2n.p}(t)+S_{3n.p}(t)+S_{4n.p}(t), \qquad (27)$$

Moreover, for a polarized echo signal that changes during radar observation of a partially polarized wave, the following ratio of Stoke's parameters takes place which characterize it's polarization structure and are random fluctuations of space and time

$$S_1^2(t) \geq S_2^2(t)+S_3^2(t)+S_4^2(t). \qquad (28)$$

If the polarization of the echo signal of a partially polarized wave remains constant during the averaging time, relation (28) will be:

$$S_1^2(t) = S_2^2(t)+S_3^2(t)+S_4^2(t). \qquad (29)$$

The echo-signal of the navigation object fluctuates but at the same time it has a deterministic component due to the presence in the general composition of reflectors with large EPR (bright dots) which over time of observation give almost non-fluctuating reflection. The echo signal of atmospheric formation is fluctuating due to the presence in the reflecting volume of a large number of elementary reflectors with spatial and temporal changes in physical properties. These two echoes are statistically independent and when added the Stoke's parameters for the case of independent radiation fluxes are equal to the sum of the corresponding parameters of the deterministic and fluctuating fluxes, i.e.

$$S_{1\Sigma}(t)=\sum_{i=1}^{N} S_{1i}(t), \quad S_{2\Sigma}(t)=\sum_{i=1}^{N} S_{2i}(t), \quad S_{3\Sigma}(t)=\sum_{i=1}^{N} S_{3i}(t), \quad S_{4\Sigma}(t)=\sum_{i=1}^{N} S_{4i}(t), \qquad (30)$$

where $S_{i\Sigma}(t)=S_{i\,n}(t)+S_{i\,fl}(t)\ \ (i=1, 2, 3, 4)$

and the coherence matrix of the total partially polarized echo signal is written as:

$$R_{\Sigma_{p.p}} = \begin{bmatrix} S_{1\Sigma}(t) \\ S_{2\Sigma}(t) \\ S_{3\Sigma}(t) \\ S_{4\Sigma}(t) \end{bmatrix}. \qquad (31)$$

To extract the navigation objects echo from an partially polarized wave, used by another remarkable property of the Stoke's parameters, is that they can be used to decompose the total partially polarized wave into the sum of two waves, one of which is completely polarized and the other is not dependent on the first, is not polarized.

In a fully polarized wave, there is a complete correlation between the orthogonal components of the electric field strength $E_x(t)$ and $E_y(t)$ included in the Stoke's parameters $S_{1\Sigma}(t)$, $S_{2\Sigma}(t)$, $S_{3\Sigma}(t)$, $S_{4\Sigma}(t)$.

In a completely non-polarized wave, there is no correlation between $E_x(t)$ and $E_y(t)$.

Fully polarized and unpolarized waves are the most common and marginal polarization state of partially polarized waves.

In a fully polarized wave, the fluctuations of the orthogonally polarized components $E_x(t)$ and $E_y(t)$ in the linear basis are time-synchronous, and their product, averaged over time, is not equal to zero, i.e.

$$\overline{E_x(t)E_y(t)} \neq 0\ . \qquad (32)$$

For a completely non-polarized wave, fluctuations of orthogonally polarized components are independent and their product which averaged over time is zero, i.e.

$$\overline{E_x(t)E_y(t)} = 0. \tag{33}$$

Based on the analysis of fully polarized and unpolarized waves in the total partially polarized wave, the Stoke's vector performs a non-chaotic and not completely ordered motion, resulting in a total partially polarized wave characterized by full intensity, consisting of the intensities of the fully polarized and non-polarized components. Since the unpolarized component in the total partially polarized wave does not have any preferential polarization, therefore the Stoke's parameters $S_{2\Sigma}(t) = S_{3\Sigma}(t) = S_{4\Sigma}(t) = 0$, and the Stokes vector of the unpolarized wave is characterized only by the full intensity I equal to the first Stokes parameter, i.e.

$$S_{unp}(t) = \lfloor S_{1\Sigma}(t), 0, 0, 0 \rfloor. \tag{34}$$

A fully polarized component of a total partially polarized wave has only one type of polarization — linear, circular, or elliptical. The Stoke's parameters of a fully polarized component of a partially polarized wave satisfy the equation:

$$S_{1\Sigma}^2(t) = S_{2\Sigma}^2(t) + S_{3\Sigma}^2(t) + S_{4\Sigma}^2(t). \tag{35}$$

In general, the Stoke's vector of a partially polarized wave can be decomposed into two components and written as a sum:

$$S(t) = S_{unp}(t) + S_{\Sigma}(t), \tag{36}$$

where $S_{unp}(t)$ is the Stokes vector of the unpolarized component of a partially polarized wave, equal to:

$$S_{unp}(t) = \left\{ \left[S_{1\Sigma}(t) - S_{2\Sigma}(t) + S_{3\Sigma}(t) + S_{4\Sigma}(t) \right]^{1/2}, 0, 0, 0 \right\}, \tag{37}$$

and the Stoke's vector of the polarized component of the total partially polarized wave is written through the Stoke's parameters in the form:

$$S_{\Sigma}(t) = \left\{ \left(S_{2\Sigma}^2(t) + S_{3\Sigma}^2(t) + S_{4\Sigma}^2(t) \right)^{1/2}, S_{2\Sigma}(t), S_{3\Sigma}(t), S_{4\Sigma}(t) \right\}. \tag{38}$$

The Stoke's parameters allow the total intensity expressed in the total partially polarized wave, expressed by the first Stoke's parameter $S_{1\Sigma}(t)$. Then the intensity of the non-polarized component is written in the form:

$$S_{unp}(t) = S_{1\Sigma}(t) - \sqrt{S_{2\Sigma}^2(t) + S_{3\Sigma}^2(t) + S_{4\Sigma}^2(t)} \tag{39}$$

and the intensity of the fully polarized component will be equal to:

$$S_{\Sigma}(t) = S_{1\Sigma}(t) - S_{unp}(t) = \sqrt{S_{2\Sigma}^2(t) + S_{3\Sigma}^2(t) + S_{4\Sigma}^2(t)}. \tag{40}$$

A non-polarized component of a partially polarized wave consists of the sum of two independent fully polarized components, which is equal in intensity, but opposite in polarity, with a specific type of polarization. The polarization of the first component corresponds to the polarization of the echo signal of the polarized component of the total partially polarized wave represented by the Stoke's parameters $\left(\sqrt{S_{2\Sigma}^2(t) + S_{3\Sigma}^2(t) + S_{4\Sigma}^2(t)}, S_{2\Sigma}(t), S_{3\Sigma}(t), S_{4\Sigma}(t)\right)$, and the polarization of the second component is orthogonal to the polarization of the echo signal of the polarized component in the total partially polarized wave. Accordingly, the echo signal of the total partially polarized wave of a navigation object located in the zone of atmospheric formation is characterized by the Stokes parameters $\{S_{1\Sigma}(t), S_{2\Sigma}(t), S_{3\Sigma}(t), S_{4\Sigma}(t)\}$ and is considered as the result of the addition of two independent fully polarized components with intensities P_1 and P_2:

$$P_1 = \frac{S_{1\Sigma}(t) + \sqrt{S_{2\Sigma}^2(t) + S_{3\Sigma}^2(t) + S_{4\Sigma}^2(t)}}{2},$$

$$P_2 = \frac{S_{1\Sigma}(t) - \sqrt{S_{2\Sigma}^2(t) + S_{3\Sigma}^2(t) + S_{4\Sigma}^2(t)}}{2}. \qquad (41)$$

The polarization of the first component with intensity P_1 of the echo signal of the total partially polarized wave coincides with the polarization of the stable polarized component of the echo signal of the navigation object and corresponds to the echo signal of the navigation object in the total partially polarized wave, and the polarization of the second component of the echo signal of the total partially polarized wave with intensity P_2, orthogonal to the polarization of the polarized echo component of the navigation object and corresponds to the echo component atmospheric formation in total partially polarized wave. After appropriate amplification and transformation into the ship's radar receiver, each of the P_1 and P_2 echo signal components of the total partially polarized wave appears on the display of the ship's computer, where the echo signal of the navigation object and the echo signal of the atmospheric formation are separately observed in the color image.

CONCLUSIONS

1. The research on the total coherence matrix of a partially polarized wave was carried out, which allowed to obtain information about its polarization state.

2. Separate intensity of the echo signals of the navigation object and atmospheric formation were obtained, which allowed their independent radar observation.

3. The solution was found on separating an echo signal of a navigation object from a total echo signal when remotely observing objects by the ship's radar system on a ship's route.

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