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Increasing the functionality of the ship's radar systems

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JEL Classification: C1, C3, R40, R41

Abstract

The purpose of this research is to develop and analyze certain technical solutions on the composition of elements and devices of the ship radar polarization complex (SRPC), increasing its functional capabilities in complex conditions of the atmospheric environment. This paper substantiates the methodology of SRPC construction, which includes a six-channel waveguide polarization splitter. The methodology of this research is aimed at solving the issues relating to the development of the main high-frequency nodes of the considered splitter and the mathematical description of the relations between the field components in the splitter. The structure of the SRPC construction defines the nature of connections and relations between the elements of the functional scheme as a whole, and the rearrangement of the structure includes methods that characterize the change in the composition and functional interaction of its parts depending on the performance of the task of polarization selection of echo-signals of the navigation object located in complex atmospheric conditions on the ship's route. Elements included in the SRPC and devices of the all-polarized antenna allow for radiating electromagnetic waves of linear and circular polarizations, as well as unpolarized waves, to analyze polarization parameters of echo signals of complex objects to solve problems of polarization selection of navigation objects located in the zone of dangerous atmospheric formations. A six-channel polarization splitter in the waveguide channel of the SRPC antenna splits the polarized components of the analyzed partially polarized wave arriving at the input of the all-polarized antenna into six channels to ensure the symmetry of its two orthogonally polarized components. The two-channel linear receiver amplifies and transforms orthogonal components of the electromagnetic wave echo signal for each polarization of the radiated wave and forms energetic actual Stokes parameters that allow for solving problems of polarization selection of navigation objects located in complex atmospheric conditions along the ship's trajectory. Polarization selection provides the formation and consistent radiation of constant power electromagnetic waves of four polarizations (three linear and one circular), as well as an unpolarized wave. As a result of the research performed on the development of a six-channel waveguide polarization splitter, the problem of increasing the efficiency of ship radar stations functioning with the use of methods of polarization selection of navigation objects and improvement of radar equipment is solved.

Introduction: Statement of the problem in general terms and its relation to scientific and practical tasks

In ship radar stations, the amplitude and phase characteristics of electromagnetic waves arriving at the antenna input cannot provide the most complete information about the navigational object located in the zone of dangerous atmospheric formations along the ship's trajectory, despite the use of two wavelength ranges $\lambda_1 = 3.2$ cm and $\lambda_2 = 10$ cm. Recent developments in meteorological radars use the same wavelength ranges as ship radars and provide meteorological information to seaports. The meteorological radars in operation in Europe after 1990, alongside the technical characteristics, peculiarities of their construction, and methods of atmospheric formation measurements, are presented in the following publications.

In the study of Divjak (Divjak, 1999), the methods of correction of measured *Z* (the vertical integral of reflectivity) values to improve the accuracy of radar estimates of precipitation and the Earth's surface in suboptimal conditions were considered. The problem of calibration and maintenance of weather radar in rainfall measurement on the European continent under COST-75 was reviewed by Koistinen and Saltikoff (Koistinen & Saltikoff, 1999). Meischner (Meischner, 1999) found that, when radar and ground data are matched, rain gauges with wind shielding only capture 70 % of the actual precipitation, dropping to only 50 % without wind shielding. In Serafin and Wilson (Serafin & Wilson, 1999), it was noted that, based on the results of the MEXRAD operational network in COST-75, the algorithms of the rainfall measurement system are satisfactory. It was determined by Smith and Kitchen (Smith & Kitchen, 1999) that measured precipitation is characterized by strong variability and, therefore, the estimation of its intensity and quantity should be based on radar measurements of its reflectivity. The echo signal from meteorological formations is a stationary, normal, and random process in which the average echo signal is independent of its power, as shown in Beyer et al. (Beyer et al., 1999). The meteorological radar network has been analyzed to enable forecasters to use radar precipitation information in weather forecasting (Cavaili, 1999). However, these publications do not reflect an important feature of primary radar data interpretation on the necessity of using its polarization as an informative parameter of an electromagnetic wave. There are no publications on the application of polarization methods for the obtaining of information about navigational objects in new additions of ship radars. The necessity of modernization of ship radars was presented in the publications considered below.

In Koshevoi and Shevchenko (Koshevoi & Shevchenko, 2018), the necessity of using ultrawideband radars for marine vessels was justified. In the paper by Lee and Pottier (Lee & Pottier, 2009), the methods of polarimetric radar imaging and processing were considered. Moreover, in the paper by Cloude (Cloude, 2009), radar polarimetry, interferometry, and polarization in remote sensing were considered. In Akinshin et al. (Akinshin et al., 2019), a simulation model of the block scheme of the radar with full polarization scanning was presented. In addition, Akinshin, Varenitsa and Khomyakov (Akinshin, Varenitsa & Khomyakov, 2016) provided a joint estimation of the coordinate and polarization parameters of radar objects. In Klemm et al. (Klemm et al., 2017a), new radar methods and applications, real aperture grating radar, imaging radar, and passive and multistatic radar were reviewed. New radar methods and applications, diversity of waveforms and cognitive radar, and target tracking and data fusion were presented in Klemm et al. (Klemm et al., 2017b). Pulsed Doppler radar, alongside the principles of its construction and applications, was presented in Alabaster (Alabaster, 2012). However, the analysis of these publications showed that the theoretical developments have not yet been implemented in practice. There is a need for a transition to polarization measurements of echo signals of partially polarized waves of complex objects and the development of ship radar polarization complexes capable not only of determining object coordinates, but also of polarization selection of navigation objects located in the zone of dangerous atmospheric formations.

Therefore, the urgent task of marine polarimetry is the development of a shipboard radar polarization complex, which makes it possible to implement the methods of polarization selection of navigational objects located in dangerous atmospheric conditions in practical shipboard radar. Construction of ship radar polarization complex implementing polarization selection of echo signals of partially polarized waves of a complex object assumes representation of polarization properties of both electromagnetic waves irradiating the complex object and electromagnetic waves reflected from the complex object and arriving at the input of all-polarized antenna SRPC by actual energy polarization parameters of Stokes, which are only formed on energy values of the echo signals of a partially polarized wave without phase measurements of the orthogonal components.

Thus, there is an obvious need to develop and substantiate the principle of SRPC construction, realizing theoretical developments of polarization analysis in the practical operation of ship radars and, thereby, increasing the safety of ship navigation in complex conditions of the atmospheric environment.

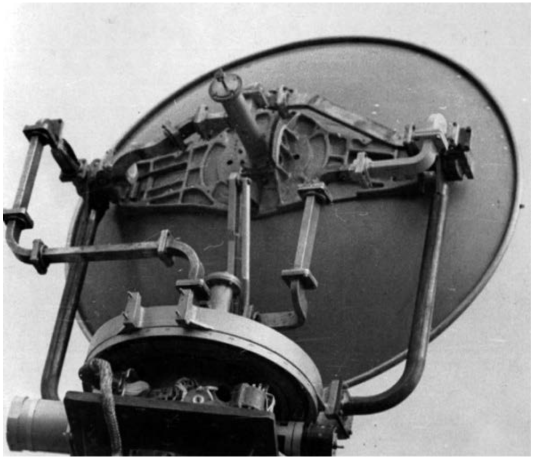
Presentation of the research methods with the substantiation of the obtained scientific results

To solve the task at hand, it is necessary to analyze the principle of SRPC construction by functional schemes, taking into account the fact that the time for which the vector amplitude of the electromagnetic field of the echo signals of a partially polarized wave, which arrives at the input of its all-polarized antenna, noticeably changes and is large compared to the period of high frequency and the time required to measure the polarization parameters of Stokes echo signal of a partially polarized wave of a complex object of radar observation. To determine the polarization parameters of the Stokes of a partially polarized wave, at least four independent measurements are made simultaneously in the SRPC, which is due to the fact that four Stokes parameters are measured at the output of a two-channel linear receiver at each irradiation of a complex object with an electromagnetic wave of a certain polarization with the decomposition of the high-frequency field received by an all-polarized antenna, which is shown in Figure 1.

The all-polarized antenna consists of a conical horn connected by means of a circular waveguide to a six-channel polarization splitter, the functional diagram of which is shown in Figure 2.

To divide the elliptically polarized wave echo signal of a complex object into two orthogonal linearly polarized components arriving at the antenna input, waveguide polarization splitter 3 on a circular waveguide with a transition from a circular cross-section to two orthogonally arranged rectangular waveguides and waveguide splitter 4 separating the elliptically polarized wave echo signal using also two rectangular waveguides with the orientation of the electric vector 45° and 135° are used. In connection with the use of linearly polarized electromagnetic waves with an inclination of the electric vector 45° and 135° by the SRPC, waveguide

a)



b)

Figure 1. Appearance of the all-polarized SRPC antenna

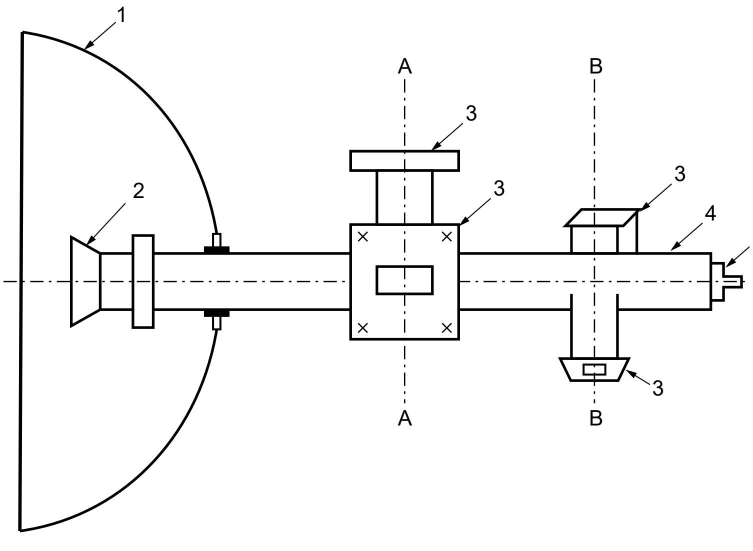


Figure 2. Waveguide separator of the echo signals of the linear polarizations: 1 and 2 – antenna with emitter; 3 – waveguide separator of echo signals on linear orthogonal polarizations; 4 – waveguide separator of echo signals on linear orthogonal polarizations with an orientation of rectangular waveguides at 45° and 135°; 5 – plunger of adjustment of waveguide separator

splitter 4 of the linearly polarized echo signal into two components, which is an extension of the circular waveguide, is employed. Waveguide splitter 4 is also a ternary transition device from the circular waveguide to two orthogonally located waveguides of rectangular cross-section, which receive linearly polarized components of echo signals, the plane of polarization of which is at an angle of 45° and 135°. The connection of these waveguides (circular and four rectangular) forms the polarization splitter itself (Figure 2). The circular waveguide of the splitter ends with tuning plunger 5, connected at a distance $\lambda/4$ from the connection point of the rectangular waveguides.

The separation of an electromagnetic wave of elliptical polarization occurs as follows. In the circular waveguide, when the wave is divided into linear components, a TE_{11}-type wave occurs, the electric field force lines of which are distributed in the cross-section of the splitter. At the entrance of rectangular waveguides, at some distance from the place of their connection to the circular waveguide, the electric field lines of force will be oriented along the narrow wall of rectangular waveguides and, thus, provide excitation of the electromagnetic wave TE_{10}, in both waveguides. If the circular waveguide from the antenna output receives a linearly polarized wave with an angle of inclination of the electric vector of 45° and 135° then, in this case too, the wave power will be divided equally in the rectangular waveguides located in waveguide splitter 4. The connection of the waveguides forming polarization splitter 3 and polarization splitter 4 is shown in Figure 2 in sections A-A and B-B, and the distribution of the electric vectors of the electromagnetic wave originating from the output of the antenna system and the connection of the waveguides in the splitters 3 and 4 is shown in Figure 3.

When arriving in receiver mode from the antenna output into the circular waveguide, an arbitrarily polarized power wave in the rectangular orthogonal channels of the splitter can be determined by the ratio of the amplitudes of the corresponding components.

To form an electromagnetic wave of elliptical polarization from the echo signal received at the input of an all-polarized antenna, an electromagnetic wave of circular polarization is used; the functional scheme is shown in Figure 4.

The all-polarized antenna of the SRPC in the receiving mode receives an echo signal of any polarization. We are interested in solving the problem of polarization selection of a navigation object located in the zone of rainfall of different intensities and the reception of an echo signal of a complex object, which has elliptical polarization (i.e., in a special case, linear and circular polarization). Let an electromagnetic wave of elliptical polarization, the electric vector of which in a circular waveguide is represented by the electric vector E of linear polarisation (Figure 3), arrive at the input of a polarization splitter in its receiving mode. Linearly polarized components of vector E' and E'' are represented in the waveguide splitter system with respect to the cross-section of rectangular waveguides, which are connected to the circular waveguide.

The design of the waveguide six-channel splitter provides the appearance of an echo signal of only one polarization component of the electromagnetic wave in one output channel of the polarization splitter block scheme, which is presented in Figure 5.

In the reception mode of the all-polarized antenna, the partially polarized echo signal of a complex object is related to the amplitudes of its orthogonally polarized components E_1 and E_2 in the far zone of the all-polarized antenna at the output of each of the six channels of the polarization

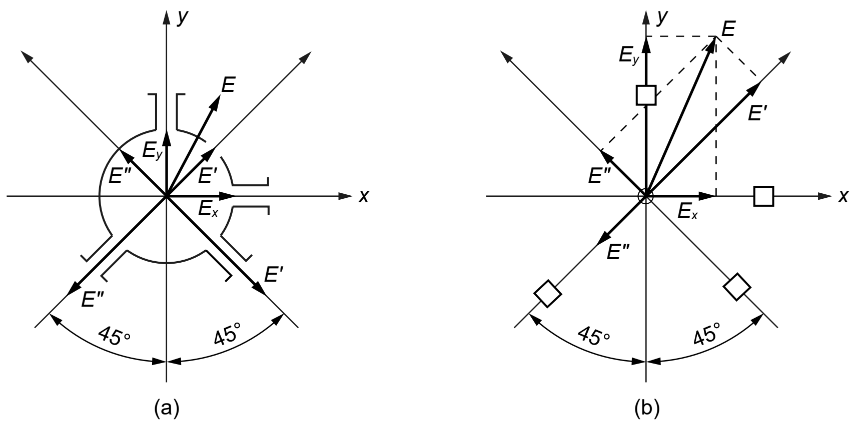


Figure 3. Connection of waveguides: vector diagrams for (a) the electric field strength distribution and (b) the waveguide splitters separated into four orthogonal components

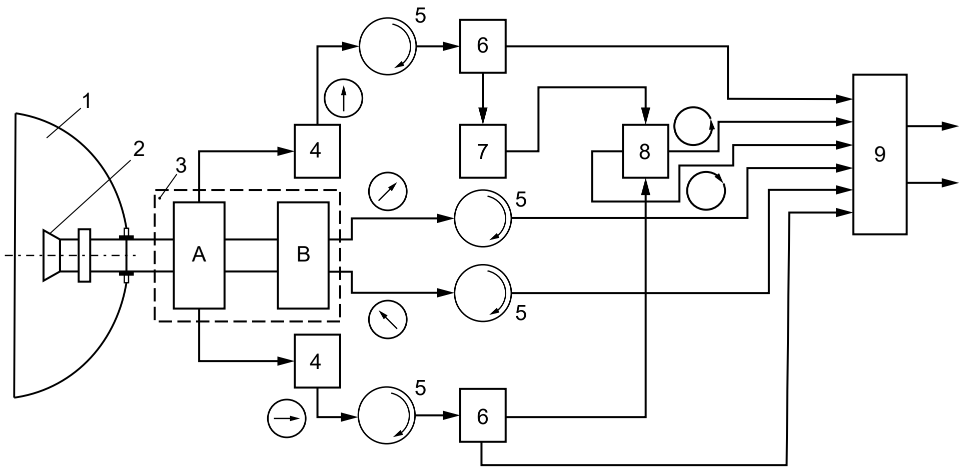


Figure 4. Functional scheme of the formation of the echo signal of the electromagnetic wave of circular polarization in a six-channel waveguide polarisation splitter: 1 and 2 – antenna with emitter; 3 – waveguide separator of echo signals of linear polarizations; 4 – antenna switches; 5 – circulators; 6 – waveguide H and E – bridges; 7 – phase shifter of linearly polarized wave of vertical polarization at 90°; 8 – waveguide T – bridge; 9 – waveguide switch. A – polarization waveguide splitter into orthogonally polarized components; B – polarization waveguide splitter on orthogonally polarized components with orientation of the electric vector at the angles 45° and 135°

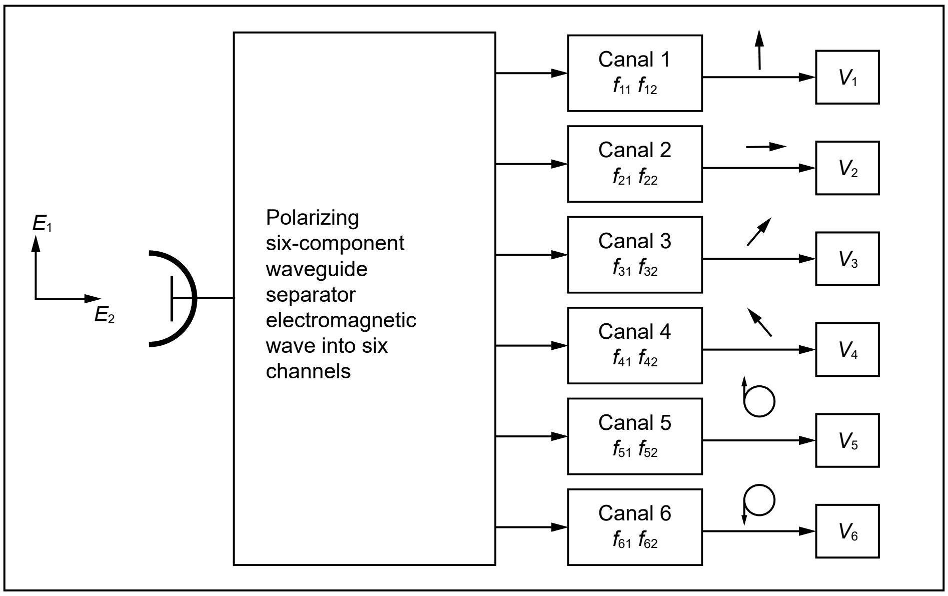


Figure 5. Block scheme of a six-channel polarization electromagnetic wave splitter into six polarized components

splitter (Figure 5), through the transmission coefficients f_{k1} and f_{k2} with the amplitudes of the normalized voltage V_1–V_6 at the output of a certain channel of the splitter, by the following dependence in the form of a matrix expression:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \\ f_{31} & f_{32} \\ f_{41} & f_{42} \\ f_{51} & f_{52} \\ f_{61} & f_{62} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} \tag{1}$$

The scattering matrix of a six-channel polarization splitter, which characterizes its performance, is written in the form:

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} & S_{37} & S_{38} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} & S_{47} & S_{48} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} & S_{57} & S_{58} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} & S_{67} & S_{68} \\ S_{71} & S_{72} & S_{73} & S_{74} & S_{75} & S_{76} & S_{77} & S_{78} \\ S_{81} & S_{82} & S_{83} & S_{84} & S_{85} & S_{86} & S_{87} & S_{88} \end{bmatrix} \tag{2}$$

The input echo signal matrix $[S]_{in}$ and the output echo signal matrix $[S]_{out}$ are of the form:

$$[S]_{\text{in}} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \\ a_7 \\ a_8 \end{bmatrix} \qquad (3)$$

$$[S]_{\text{out}} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \\ b_7 \\ b_8 \end{bmatrix} \qquad (4)$$

In this case, the relationship of input signal matrix (3), output signal matrix (4), and scattering matrix (2) is established by the following equation:

$$[S]_{out} = [S][S]_{in} \qquad (5)$$

The diagonal coefficients of the scattering matrix [*S*] of the six-channel polarization splitter are the reflection coefficients of the *k*-th channel when the other channels are matched. When the other channels of the matrix are matched, there are no couplings between the input and output waves in each of the splitter arms. This condition leads to an equality to zero of all the diagonal elements of the scattering matrix [*S*]. Taking this into account, we can write:

$$\left.\begin{array}{l} S_{12} = S_{21} = S_{34} = S_{43} = S_{56} = S_{65} = S_{78} = S_{87} = 0 \\ S_{11} = S_{22} = S_{33} = S_{44} = S_{55} = S_{66} = S_{77} = S_{88} = 0 \end{array}\right\} \qquad (6)$$

Then, the scattering matrix (2) of an ideal six-channel lossless polarization splitter is written as (7).

Let us write the scattering matrix of the separator for linear components $[S]_{lc}$ as (8).

The analysis is carried out using the linear polarization basis, whose real orthogonal polarizations are parallel to the real amplitude vectors of the first orthogonal polarizations. For linear polarizations, the scattering matrix of the splitter is unity.

$$[S] = \begin{bmatrix} 0 & 0 & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} \\ 0 & 0 & S_{23} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} \\ S_{31} & S_{32} & 0 & 0 & 0 & 0 & 0 & 0 \\ S_{41} & S_{42} & 0 & 0 & 0 & 0 & 0 & 0 \\ S_{51} & S_{52} & 0 & 0 & 0 & 0 & 0 & 0 \\ S_{61} & S_{62} & 0 & 0 & 0 & 0 & 0 & 0 \\ S_{71} & S_{72} & 0 & 0 & 0 & 0 & 0 & 0 \\ S_{81} & S_{82} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (7)$$

$$[S]_{lc} = \begin{bmatrix} 0 & 0 & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} \\ 0 & 0 & S_{23} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} \\ S_{31} & S_{32} & 0 & 0 & 0 & 0 & 0 & 0 \\ S_{41} & S_{42} & 0 & 0 & 0 & 0 & 0 & 0 \\ S_{51} & S_{52} & 0 & 0 & 0 & 0 & 0 & 0 \\ S_{61} & S_{62} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (8)$$

The formation of circular polarizations is performed by the separation of linear components into linear vertical by a linear waveguide *H*-bridge with a signal phase delay of 90° and *E*-bridge into horizontal polarization with the subsequent feeding of signals of these components to the *H* and *E* inputs of a double waveguide *t*-piece, at the output of symmetrical arms of which waves of circular polarizations of the right and left directions of rotation are formed. The scattering matrix of the double waveguide tee $[S]_{tee}$ is written as:

$$[S]_{\text{tee}} = \begin{bmatrix} 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 & 0 \end{bmatrix} = \frac{\sqrt{2}}{2} \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{bmatrix} \qquad (9)$$

For each of the eight channels of the polarization splitter with transmission coefficients f_{km} (Figure 5), connecting the voltage amplitude at the output of a certain channel with the amplitudes of orthogonally polarized components of the echo signal of the electromagnetic wave in the far zone of the all-polarized antenna of the SRPC, we can write the following equations, which will be valid only if all the outputs of the polarization splitter are matched. Then, for each channel, the dependence of the output voltage on the polarization of the analyzed wave is written in the form:

$$\begin{array}{ll} V_1 = f_{11}E_1 + f_{12}E_2 & V_5 = f_{51}E_1 + f_{52}E_2 \\ V_2 = f_{21}E_1 + f_{22}E_2 & V_6 = f_{61}E_1 + f_{62}E_2 \\ V_3 = f_{31}E_1 + f_{32}E_2 & V_7 = f_{71}E_1 + f_{72}E_2 \\ V_4 = f_{41}E_1 + f_{42}E_2 & V_8 = f_{81}E_1 + f_{82}E_2 \end{array} \quad (10)$$

To calibrate the polarization splitter for a particular channel, the ratio of amplitudes of signals measured at the outputs of different channels can be used. The amplitude of the first channel is taken as the output amplitude, then the dependence of the ratio of the amplitudes of each channel of the six-channel splitter to the amplitude of the first channel is written as follows:

$$\begin{array}{ll} \frac{V_2}{V_1} = \left|\frac{f_{21}E_1 + f_{22}E_2}{f_{11}E_1 + f_{12}E_2}\right| & \frac{V_6}{V_1} = \left|\frac{f_{61}E_1 + f_{62}E_2}{f_{11}E_1 + f_{12}E_2}\right| \\ \frac{V_3}{V_1} = \left|\frac{f_{31}E_1 + f_{32}E_2}{f_{11}E_1 + f_{12}E_2}\right| & \frac{V_7}{V_1} = \left|\frac{f_{71}E_1 + f_{72}E_2}{f_{11}E_1 + f_{12}E_2}\right| \\ \frac{V_4}{V_1} = \left|\frac{f_{41}E_1 + f_{42}E_2}{f_{11}E_1 + f_{12}E_2}\right| & \frac{V_8}{V_1} = \left|\frac{f_{81}E_1 + f_{82}E_2}{f_{11}E_1 + f_{12}E_2}\right| \\ \frac{V_5}{V_1} = \left|\frac{f_{51}E_1 + f_{52}E_2}{f_{11}E_1 + f_{12}E_2}\right| & \frac{V_9}{V_1} = \left|\frac{f_{91}E_1 + f_{92}E_2}{f_{11}E_1 + f_{12}E_2}\right| \end{array} \quad (11)$$

The practical task of tuning a polarization splitter, which is characterized by the absence of waves reflected from the inputs of a two-channel linear receiver, is reduced to measuring the voltage amplitudes at the outputs of all the channels.

Conclusions and prospects for further research in this area

1. The principle of construction of the fundamental units of the experimental ship's radar polarization complex (SRPC), which includes a six-channel waveguide polarization splitter of echo-signals of objects, which allows for the realization of the methods of polarization selection of navigation objects located in the zone of dangerous atmospheric formations along the ship's route, has been developed.
2. The developed functional scheme for the all-polarized antenna allows us to perform all of the polarization measurements on a six-channel waveguide polarization splitter, which contains six identical amplitude channels for processing and registration of echo signals of partially polarized electromagnetic waves of a complex object of radar observation.
3. The construction principle and functional scheme of a six-channel polarization waveguide polarization splitter of a partially polarized electromagnetic wave, received at the input of an omnipolarized SRPC antenna, have been developed. Its operation is justified by the waveguide scattering matrix, which establishes the relationships between the components of the electromagnetic field in different arms of the polarization splitter.
4. The methodology and polarization methods developed and implemented in the SRPC were based on the relationship between the polarization structure of the electromagnetic field at its emission and receiving with certain polarization parameters at the output and input of the all-polarized antenna and radar information processing system.
5. The problem of increasing the functional capabilities of ship radar complexes has been solved, which provides the safety of the ship's route along a given trajectory in conditions of dangerous atmospheric interference. The results of the performed research were implemented in the experimental sample of the SRPC. The experiment consisted of the simultaneous operation of two radar stations: AMRC "Meteocell" serving Zaporizhzhya airport and Azov Sea with radar information and mobile experimental complex SRPC. Automated meteorological radar complex (AMRC) "Meteocell" is designed to automate meteorological radar MRL-5 in order to provide airports and automated air traffic control systems with information about cloud cover and related dangerous weather phenomena with high reliability and efficiency. A comparative analysis of the received radar information of the AMRC "Meteocell" and the experimental SRPC of the complex was also carried out, which coincided with a probability of 95 %.

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