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PROPOSALS TO IMPROVE THE INFORMATION CAPABILITIES OF COASTAL-BASED RADAR STATIONS FOR SURVEILLANCE OF SURFACE AND AIR OBJECTS

Annotation. Sea-based radar stations (RS) are widely used for solving the tasks of radar surveillance of surface objects (SO) and air objects (AO). **The subject** of the article is the mechanisms of radio wave propagation in the boundary layer of the atmosphere. **The aim** is to investigate the possibilities of improving the accuracy of measuring the range and radial velocity of SO and AO observed beyond the line-of-sight of coastal-based RS. **Objective**: to analyse the spatial and temporal parameters and properties of waveguide layers above the water surface. **Methods** used: maximum likelihood and frequency. The following **results** were obtained. The results of experimental studies of seasonal and daily changes in the parameters of the lower troposphere layer in the Black Sea coastal zone and the parameters of tropospheric radio waveguides are presented. The procedure for calculating the energy transmission losses during radio wave propagation in the boundary layer of the atmosphere is presented, and the conditions for detecting SO and AO beyond the radar line-of-sight are determined. Recommendations for increasing the range of detection of SO and AO are given, which are associated with the possibility of predicting the existence of tropospheric radio waveguides by using data on the current conditions of radio wave propagation over the sea based on the signals of the automatic ship identification system AIS. **Conclusions**. Proposals have been developed to improve the accuracy of measuring the range and radial velocity of SO and AO at waveguide propagation of radio waves over the sea surface. **A promising area** for further research may be to identify ways to optimise the measurement of angular coordinates in modern RS during waveguide propagation of radio waves over the sea surface.

Keywords: radar station; coastal basing; radar signal; surface object; air object; tropospheric radio waveguide; range; radial velocity; phase fluctuations; frequency modulation.

Introduction

Problem formulation. The range of detection of surface objects (SO) and air objects (AO) observed by coastal-based radar stations (RS) is in most cases limited to the line-of-sight range. Increasing the detection range of RS by raising the antenna may not always be considered appropriate, due to the possible lack of dominant heights in the sea coastal areas.

The experience of operating radio systems for various purposes located on the seacoast indicates that their range of operation can vary significantly depending on the season and time of day. Reflections from local objects and low-altitude objects beyond the line of sight were recorded. This phenomenon is associated with the emergence of super refractive propagation of radio waves due to the existence of tropospheric radio waveguides (TRW), which can lead to a significant increase in the range of coastal-based RS. At the same time, the atmospheric refractive properties in the lower troposphere can change rapidly within wide limits. The search for ways to increase the range of detection of SO and AO in sea areas is relevant for surveillance RS, due to their widespread use to solve the problems of radar observation of such objects at long distances.

Increasing the range of coastal-based RS by using the peculiarities of tropospheric propagation of radio waves over the sea surface requires timely information about the current state of the troposphere. Therefore, an important scientific task is to find reliable additional sources of this information.

One of these sources is the signals of the Automatic Identification System (AIS), which can be used to predict the occurrence of over-the-sea TRW and increase the detection range of SO and AO of coastal and sea-based RS.

The use of the mechanism of super refractive propagation of radio waves is accompanied by the occurrence of fluctuation phenomena that have a significant impact on the quality of radar information. The above indicates the need to find ways to ensure the required accuracy of measuring the coordinates and parameters of the movement of SO and AO radar surveillance, in particular their range and radial velocity.

It is suggested to solve this problem by using frequency-modulated signals in coastal-based RS.

Analysis of the latest research and publications

The use of this effect of radio wave propagation beyond the line of sight requires the ability to predict the appearance of TRW over the sea surface.

In [1], the issue of diagnosing the conditions of radio wave propagation in the troposphere is considered, and their use in relation to tropospheric radio wave propagation over the sea surface is discussed in [2]. For example, [3] proved the possibility of increasing the detection range of low-altitude AO by using over-the-sea radio waveguides. However, the practical implementation of this possibility in relation to coastal-based RS is associated with timely receipt of information on the composition and state of the troposphere.

An experimental study of these issues is devoted to [3], where the dependence of the conditions for the appearance of near-surface and submerged radio waveguides on the season is established.

Therefore, measures to obtain information on the current state of the troposphere require the use of additional atmospheric sensors, which is a complex and costly task from a technical and economic point of view.

Therefore, an additional source of information about the possibility of ensuring waveguide propagation of electromagnetic waves in the troposphere is the use of signals from the automatic identification system AIS, which is mandatory for all ships in accordance with the International Convention for the Safety of Life at Sea.

Determination of the coordinates and parameters of the motion of SO and AO beyond the line-of-sight range is accompanied by significant losses due to significant fluctuations in the phase front of the radar signal wave as it propagates through the troposphere inhomogeneities. For example, an analysis of the decrease in the accuracy of measuring the angular coordinates of aerodynamic objects by three-coordinate radars depending on the degree of distortion of the phase front of the radar signal wave is given in [4], and the possible values of the RMS errors of their measurement are given in [5, 6].

The effect of random phase distortions of a radar signal on reducing the accuracy of its Doppler frequency measurement is discussed in [7, 8], and the possible transformation of the normalised frequency ambiguity function and deterioration of the quality of radar frequency resolution is analysed in [9]. At the same time, the components of the RMS errors of measuring the radial velocity of objects by survey radars and their tracking beyond the line-of-sight range are given in [10].

Consequently, it is necessary to take measures to compensate for the influence of signal fluctuations to improve the accuracy of measuring the coordinates and parameters of the movement of SO and AO detected at a long range, when waveguide radio waves propagate over the sea surface.

The optimal measurement of the Doppler frequency, accounting for the influence of correlated phase fluctuations in relation to a packet of unmodulated radio pulses, was considered in [11]. However, this type of radio signal does not provide high accuracy of range measurement, especially when radio waves propagate over the horizon. Therefore, it is expedient to solve the problem of statistical optimisation of Doppler frequency measurement by considering the fluctuations of the phase front of the radar signal wave when using frequency modulation in it. This will simultaneously ensure high accuracy of measuring the range and radial velocity of radar surveillance objects.

Moreover, the solution to this problem should be consistent with the data obtained experimentally [12].

The aim of the article is to study the possibilities of improving the accuracy of measuring the range and radial velocity of SO and AO observed beyond the line-of-sight of coastal-based RS.

Summary of the main material

In radar surveillance, SO and AO distinguish between different mechanisms of radio wave propagation in the boundary layer of the atmosphere. The predominant impact of each of them depends on climatic conditions, radio frequency, observation time, distance, and topography of the route. Either one or several mechanisms of radio wave propagation can operate simultaneously [13, 14].

The main mechanisms of radio wave propagation can be identified as the following: line of sight, diffraction, tropospheric scattering, surface waveguides, reflection, and diffraction from the underlying layer, scattering on hydrometeors.

Determining the impact of each of these mechanisms at the level of engineering calculations can be performed according to the recommendations of the International Telecommunication Union [15].

Surface waveguides are the most important mechanism for radio wave propagation, which can provide increased signal strength over long distances. Under certain circumstances, the signal strength can exceed the equivalent signal strength in “free space”.

The strongest anomalies in the propagation of radio waves are associated with the underlying atmospheric formations, the so-called layers. Information about them was obtained by direct refractometric measurements. The research results [1, 15] relate to large stable layered formations with horizontal dimensions of tens to hundreds of kilometres and a vertical gradient within the layer above the critical one.

According to the measurements, within a height of 1.5 km above the sea surface, there may be one, and occasionally two, stable layers at the same time. The layers can be both horizontal and inclined, and their height can change quite rapidly (about (50-100) m in 10 minutes).

If these changes occur in different areas asynchronously, the slope of the layer changes accordingly. Layers are detected at different times of the year. However, they are most often observed in summer and autumn.

Fig. 1 shows the relative distribution of tropospheric layers *V* by heights *h* over the three-year measurement period.

The histogram has a pronounced maximum in the altitude range of 200-500 m (the analysis area is shown by the dashed line), which corresponds to approximately 50 % of all recorded layered formations, although seasonal altitude distributions can differ significantly.

Fig. 2 shows histograms of the average height distribution of layered formations *V* in summer and autumn months. The histogram shows that in the summer months (Fig. 2, a) the tropospheric layers are located near the underlying surface, forming a clear maximum in the range of 200-300 m, and at an altitude of 1.5 km and above, layers of the second tier may appear.

The autumn season (Fig. 2, b) is characterised by the absence of tropospheric layers near the surface and a more even distribution in the rest of the altitude range.

A similar pattern was repeated during the three years of measurements, and the height distributions for the winter and spring seasons are not shown due to the small number of observed layers.

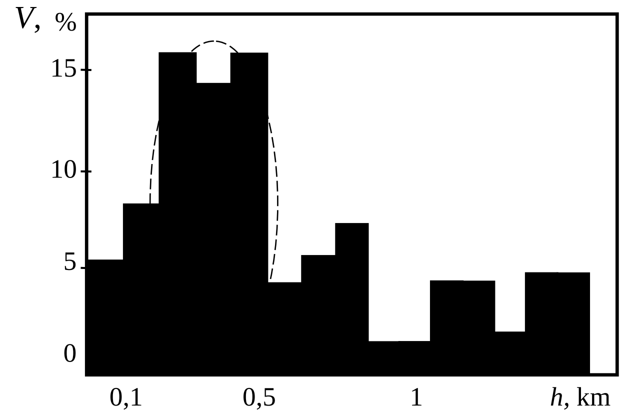

Fig. 1. Relative distribution of tropospheric layers by height for the measurement period of three years

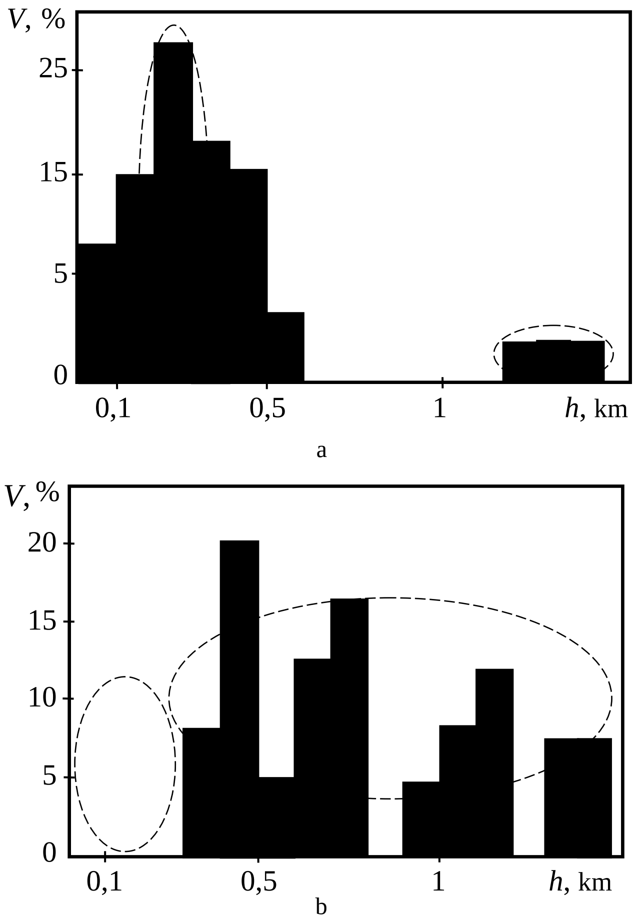

Fig. 2. Altitudinal distribution of layered formations: a – in summer; b – in autumn

The experimental data show that the average layer thickness is about 85 m and varies between 10 and 250 m. At the same time, in 76% of the observations, the layers were between 20 m and 100 m thick.

The deviation of the average refractive index gradient from the standard value in certain sections of the height profile can be not only different, but also opposite in sign. Experimental studies of meteorological parameters in the coastal areas of the Black Sea and above the sea show that there are certain regularities in the annual course of meteorological parameters in the Black Sea area. These regularities are reduced to the fact that there are stable wind roses in the Black Sea basin, which lead to the formation of the TRW.

The characteristic dynamics of radio waveguide development is illustrated in Fig. 3.

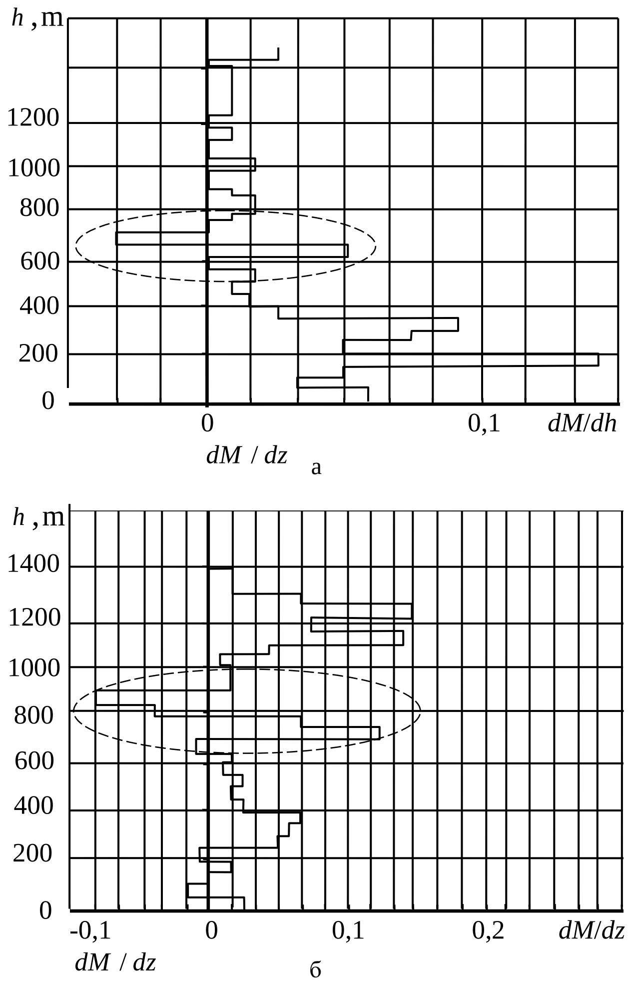

Fig. 3. Dependences of the gradient of the modified refractive index *dM*/*dh* on the height *h*, which were observed: a – in the morning; b – at noon

Fig. 3 shows the dependence of the gradient of the modified refractive index on the height *h*, which was obtained [3, 13]: a – in the morning; b – at noon.

From the data provided, it can be concluded that in the morning, a radio waveguide with an upper limit of 700 m was observed. The data recorded at noon indicate the occurrence of a radio waveguide with an upper limit of 950 m and a thickness of about 100 m in the observation area.

This data corresponds to a change in the sign of the modified refractive index gradient.

Waveguides were observed more frequently in summer. In autumn and spring, the frequency of their observation decreased compared to summer. The least frequent waveguides were recorded in winter.

Below, we can consider the conditions for detecting objects beyond the line-of-sight range of the RS. Radar stations detect SO and AO within the line of sight. Therefore, for radars, the main transmission loss is defined as [13, 14]:

$$L_{bRS} = 103,4 + 20\log f_{RS} + \\ +40\log d_{RS} - 10\log \sigma_{\mu}, \quad (1)$$

where f_{RS} is the operating frequency of the RS (MHz); d_{RS} is range to the object under observation (km); σ is effective scattering area (ESA) of the object (m^2).

The numerical value of L_{bRS} is derived from the tactical and technical characteristics of a particular type of radar.

To assess the conditions of radio wave propagation on surface (drive) routes in the sea, it is advisable to use pilot signals that must fulfil certain conditions:

– have a priori known spectral characteristics.

– the characteristics of the transmitter and the antenna-feeder system must be known in advance and sufficiently stable in time.

– the coordinates of the transmitter must be known in advance or obtained directly during signal reception.

In cases where RS are located on the coast, it may be appropriate to use signals emitted by commercial vessels' radio equipment as pilot signals.

In particular, the signals of the automatic identification system AIS.

For the studied AIS system, the route is over-the-horizon and the main transmission losses L_{bAIS} will consist of free-space transmission losses L_{bfAIS} and diffraction losses L_{bdAIS}:

$$L_{bAIS} = L_{bfAIS} + L_{bdAIS}. \quad (2)$$

Detection of RS objects beyond the line-of-sight range is possible at ranges at which the following conditions are met:

$$L_{bAIS} \le L_{bRS}.$$

The level of losses can be calculated according to the methods set out in the Recommendations of the International Telecommunication Union [16].

In accordance with the International Convention for the Safety of Life at Sea, since 2000, all ships have been required to have automatic identification systems (AIS) that are capable of

– provide information automatically to appropriately equipped coastal stations, other vessels, and aircraft, including ship identification, type, position, course, speed, navigation status and other safety-related information.

– receive such information automatically from similarly equipped vessels.

– monitor and track vessels.

– exchange data with coastal stations.

AIS transmitters should be installed:

– on all ships with a gross tonnage of 300 tonnes or more engaged in international voyages.

– on cargo ships with a gross tonnage of 500 tonnes or more that do not carry out international ships.

– on all passenger ships regardless of size.

The use of TRW, data on which can be obtained by analysing the parameters of the signals of the AIS ship identification system, can significantly increase the RS detection range of coastal-based objects.

The wave-like nature of radio wave propagation in sea waters leads to changes in detection quality indicators, and this is of the highest quality if the RS antenna and the SO (AO) are located inside the TRW for the best use of its directional properties [12].

Thus, the use of information on the state of the troposphere with the ability to determine the existence of a TRW by signals from the automatic identification ship system AIS helps to increase the range of detection of radar observed SO and AO.

In modern radars, a coherent packet of radio pulses is widely used as a sensing signal, which provides a sufficiently high quality of time-frequency processing and the required accuracy of Doppler frequency determination.

However, when carrying out radar surveillance beyond the line-of-sight range, it is necessary to consider the phase fluctuations of the received radio pulses due to a significant decrease in the accuracy of measuring the coordinates and parameters of the movement of the AO and SO.

The problems of optimal measurement of the range and radial velocity of SO and SO in a coherent pulse RS with consideration of random phase distortions of the packet radio signal are presented in [11].

While the required accuracy of radial velocity measurement can be achieved by using a coherent packet of radio pulses, the accuracy of range measurement is determined by the spectral width of the RS probing signal. This indicates the expediency of improving the accuracy of measuring the range to SO and AO [17–20].

For this reason, the analysis of the possibilities of accounting for random phase distortions in a frequency-modulated radar signal when measuring the radial velocity of SO and AO observed beyond the radar line of sight is considered below.

For comparison purposes, it is advisable to first analyse the possibilities of considering random wavefront distortions in a radio signal without internal modulation, and then proceed to this analysis for a radio signal with internal frequency modulation.

It is assumed that SO or AO is irradiated by a radio signal described by the following expression:

$$u(t) = \mathrm{Re}\left\{\dot{U}(t)e^{j\omega_0 t}\right\}, \quad (3)$$

where $\dot{U}(t) = \left|\dot{U}(t)\right|e^{j\psi(t)}$ is complex signal envelope; $\omega_0 = 2\pi f_0$ – cyclic carrier frequency; f_0 is carrier frequency; t is current time; $\psi(t)$ is signal phase change over time.

The radar-observed movement of the SO (AO) causes a change in the time scale of the emitted signal by a value:

$$\gamma = \frac{2\upsilon_r}{c}, \quad (4)$$

where υ_r is the radial velocity of the object; c is the speed of light.

Then, the received signal can be recorded as follows:

$$u\left[(1+\gamma)t\right] = \mathrm{Re}\left\{\begin{array}{c}\left|\dot{U}\left[(1+\gamma)t\right]\right| e^{j\psi\left[(1+\gamma)t\right]} \times \\ \times e^{j\varphi_0} e^{j\omega_0\left[(1+\gamma)t\right]}\end{array}\right\}, \quad (5)$$

where φ_0 is random initial phase.

Information about the Doppler frequency F_d is contained in the phase difference of the emitted (3) and received (5) signals, which can be considered as the expected signal in the measurement algorithm:

$$x(t,\gamma) = \left[\omega_0 \gamma t + \Delta\psi(t) + \varphi_0\right] rect(t/T), \quad (6)$$

where $\Delta\psi(t) = \psi\left[(1+\gamma)t\right] - \psi(t)$; $rect(t/T)$ is the rectangular pulse of unit height and duration T, the centre of which corresponds to the moment $t = 0$; T is the observation interval within which the random initial phase is considered.

Given that $\gamma << 1$ and that

$$\gamma\omega_0 = \Omega = 2\pi F_\partial ,$$

то the expected signal can be represented as follows:

$$x(\Omega, t, \varphi_0) = \left[\Omega t + \varphi_0\right] rect\left(\frac{t}{T}\right). \quad (7)$$

According to this view, random distortions of the signal phase front can be considered as additive interference with the useful signal:

$$y(\Omega, t, \varphi_0) = x(\Omega, t, \varphi_0) + n_\varphi, \quad (8)$$

where n_φ is random distortion of the signal phase front.

Measurement of signal parameters involves finding the natural logarithm of the likelihood ratio [21, 22]:

$$\ln \ell\left[y(\Omega, t, \varphi_0)\right] = \int_{-\infty}^{\infty} y(\Omega, t, \varphi_0) r(\Omega, t) dt - q^2(\Omega, t)/2. \quad (9)$$

In expression (9), the signal-to-noise ratio by power is determined by the expression:

$$q^2(\Omega, t) = \int_{-\infty}^{\infty} x(\Omega, t, \varphi_0) r(\Omega, t) dt. \quad (10)$$

Relations (9) and (10) contain the weight function $r(\Omega, t)$, which can be found using the integral equation of the following form:

$$\int_{-\infty}^{\infty} \Phi(t, s) r(\Omega, s) ds = x(\Omega, t, \varphi_0), \quad (11)$$

where $\Phi(t, s)$ is the correlation function of random fluctuations of the received radio signal phase front.

Fluctuations of the radar signal phase front are assumed to be distributed according to a normal law with zero mean as follows [23]:

$$p(\varphi_0) = \frac{1}{\sqrt{2\pi\sigma_\varphi^2}} \exp\left(-\varphi_0^2 / 2\sigma_\varphi^2\right), \quad (12)$$

where σ_φ^2 is the dispersion of the radar signal phase front fluctuations. Thus, considering these fluctuations of the phase front consist in calculating the average likelihood ratio of the form:

$$\ell\left[y(\Omega, t)\right] = \int_{-\infty}^{\infty} \ell\left[y(\Omega, t, \varphi_0)\right] p(\varphi_0) d\varphi_0. \quad (13)$$

When irradiating the SO (AO) by a frequency modulated radio signal, it is described by the expression:

$$u(t) = \mathrm{Re}\left\{\left|\dot{U}(t)\right| e^{jbt^2} e^{j\omega_0 t}\right\}, \quad (14)$$

where $b = \Delta\omega/T$ is the angular modulation parameter; $\Delta\omega$ is the deviation of the cyclic frequency of the signal. In this case, the expected signal (7) takes the following form:

$$x(\Omega, t, \varphi_0) = \left[\Omega\left(t + \frac{k}{T}t^2\right) + \varphi_0\right] rect\left(\frac{t}{T}\right), \quad (15)$$

where $k = \Delta\omega/\omega_0$ is the relative broadband of the frequency modulated signal.

From (15), at $k = 0$ the expected signal with frequency modulation transitions to the unmodulated expected signal (7).

It is considered the case when the influence on the radar signal is carried out by a phase front fluctuation, the correlation of which is described by an exponential function according to the formula [24]:

$$\Phi(\tau) = \sigma_\varphi^2 \exp\left(-\tau/\rho\right), \quad (16)$$

where τ is the observation interval of the correlation function of the signal phase front fluctuations; ρ is the correlation interval of the signal phase front fluctuations.

The correlation function (16) is the simplest case of statistical description of correlated phase fluctuations of a radar signal, which, however, is consistent with the results of theoretical and experimental studies [25, 26].

In this case, the integral equation (11), considering (15) and (16), can be written in the following form:

$$\sigma_\varphi^2 \int_{-T/2}^{T/2} e^{-|t-s|/\rho} r(\Omega, s) ds = \left[\Omega\left(t + \frac{k}{T}t^2\right) + \varphi_0\right] rect\left(\frac{t}{T}\right), \quad (17)$$

Due to the presence of the influence of correlated fluctuations of the radar signal wave front, the weight function $r(\Omega, t, \varphi_0)$ should be considered as the sum of:

$$r(\Omega, t, \varphi_0) = \Omega r_0(t) + \varphi_0 r_\varphi(t), \quad (18)$$

where $r_0(t)$ is the weighting function for a signal with fully known parameters, except for the measured one; $r_\varphi(t)$ is the weighting function for a signal with a random initial phase.

Eliminating complex intermediate mathematical transformations, the components of the weighting function (18) are as follows:

$$r_0(t) = 1\Big/\left(2\rho\sigma_\varphi^2\right)\times$$
$$\times\left\{\begin{array}{c}\left[t + k\dfrac{t^2}{T} + 2\rho^2\dfrac{k}{T}\right]rect\left(\dfrac{t}{T}\right) + \\ +\left(\rho^2 + \dfrac{\rho T}{2}\right)\left[\delta\left(t - \dfrac{T}{2}\right) - \delta\left(t + \dfrac{T}{2}\right)\right] + \\ +k\left(\rho^2 + \dfrac{\rho T}{4}\right)\left[\delta\left(t - \dfrac{T}{2}\right) + \delta\left(t + \dfrac{T}{2}\right)\right]\end{array}\right\}, \quad (19)$$

$$r_\varphi(t) = \frac{1}{2\rho\sigma_\varphi^2}\times$$
$$\times\left\{rect\left(\frac{t}{T}\right) + \rho\left[\delta\left(t - \frac{T}{2}\right) + \delta\left(t + \frac{T}{2}\right)\right]\right\}, \quad (20)$$

where δ is delta function.

By using (12) and (18) and considering (19) and (20), it is possible to obtain the natural logarithm of the likelihood ratio (13) as a function of the measured parameter $\ln \ell(\Omega)$ for a frequency modulated radio signal.

Estimating the error dispersion of the Doppler frequency measurement is possible by the method of maximum likelihood [27] using the following expression:

$$\frac{1}{\sigma_\Omega^2} = -\frac{d^2 \ln \ell(\Omega)}{d\Omega^2}. \quad (21)$$

After double differentiation of the natural logarithm of the likelihood ratio by frequency, the expression for determining the dispersion of the error of Doppler frequency measurement, according to (21), can be written in the following form:

$$\sigma_\Omega^2 = \frac{\sigma_\varphi^2}{T^2}\left\{\begin{array}{c}1/\left(12\nu\right) + \nu/4 + 1/4 + k^2\times \\ \times\left[\dfrac{1}{80\nu} + \dfrac{\nu}{12} + \dfrac{1}{16} - \dfrac{\left(1/(6\nu) + 1/2\right)^2}{4\left(1/\nu + 1\right)}\right]\end{array}\right\}^{-1}, \quad (22)$$

where $\nu = 2\rho/T$ is the relative correlation interval of the signal phase fluctuations.

In practice, it is convenient to use the normalisation of the functions under study [28]. Therefore, it is advisable to proceed to the normalised dispersion of the Doppler frequency measurement error by the expression:

$$\sigma_{\Omega n}^2 = \frac{\sigma_\Omega^2}{\sigma_\varphi^2}T^2 = \left\{\begin{array}{c}\dfrac{1}{12\nu} + \dfrac{\nu}{4} + \dfrac{1}{4} + k^2\times \\ \times\left[\dfrac{1}{80\nu} + \dfrac{\nu}{12} + \dfrac{1}{16} - \dfrac{\left(\dfrac{1}{6\nu} + \dfrac{1}{2}\right)^2}{4\left(\dfrac{1}{\nu} + 1\right)}\right]\end{array}\right\}^{-1}. \quad (23)$$

In Fig. 4 shows the graphs of the dependence of the normalised dispersion $\sigma_{\Omega n}^2$ on the relative correlation interval of phase fluctuations at fixed values of the relative broadband of the signal with frequency modulation k ($k = 0{,}1$; 0,5; 1).

From the graphs, the maximum value of the Doppler frequency measurement error dispersion is observed in the proximity of $\nu = 0{,}5$ and is almost independent of the relative frequency modulated signal broadband.

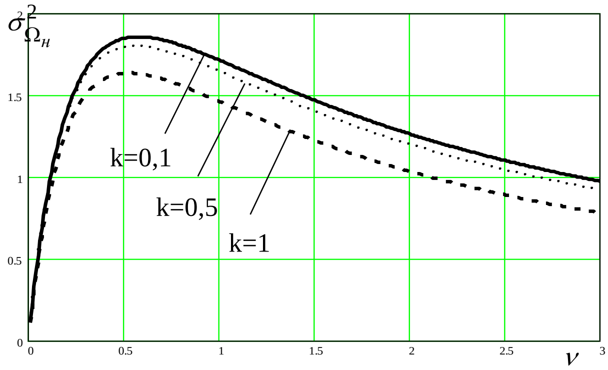

Fig. 4. Dependence of the normalised dispersion of the Doppler frequency measurement error on the relative correlation interval of the phase fluctuations of the signal

At $\nu < 0{,}5$ the normalised variance $\sigma_{\Omega n}^2$ decreases, which is explained by smoothing the fluctuations of the signal phase front. The decrease in $\sigma_{\Omega n}^2$ at $\nu > 0{,}5$ is explained by the fact that an increase in the relative correlation interval ν causes a slowdown in the phase fluctuations of the signal with frequency modulation, i.e., an improvement in its coherence.

Fig. 5 shows the graphs of the dependence of this normalised variance $\sigma_{\Omega n}^2$ on the value of k at fixed values of ν ($\nu = 1$; 2; 4). From the above graphs, with an increase in relative broadband, the normalised variance of the Doppler frequency measurement error $\sigma_{\Omega n}^2$ decreases approximately equally for different values of the relative correlation radius ν. This indicates the expediency of using signals with larger values of frequency deviation.

According to the data given in [11], it is determined that the increase in the accuracy of measuring the Doppler frequency by taking into account the fluctuations of the phase front with an exponential correlation function when using a coherent packet of radio pulses as a probing signal under normal conditions of radar operation is up to 20 %, and in the conditions of the disturbed state of the troposphere, the significant influence of the earth (sea) surface and the performance of SO and AO manoeuvring - can be about 4 times.

It is known that the potential accuracy of measuring the range of radar objects is determined by the width of the radar signal spectrum, which, in the case of frequency modulation, is determined by the frequency deviation [29].

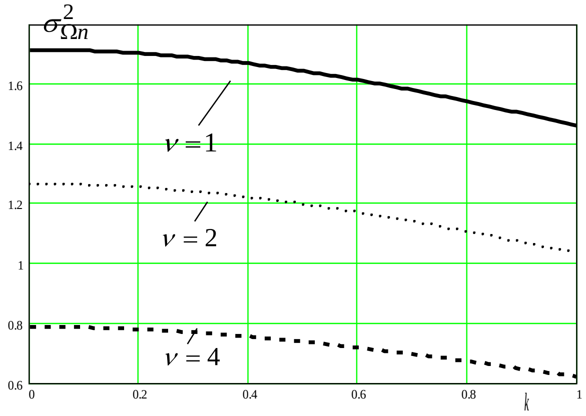

Fig. 5. Dependence of the normalised dispersion of Doppler frequency measurement error on relative signal broadband with frequency modulation

When jointly determining the range and radial velocity of SO and AO, the dispersion of their errors, in the presence of correlation between them, exceeds the corresponding values of the separate measurement. This is typical for signals with sloped uncertainty diagrams, which include signals with frequency modulation [30]. For example, for a signal with linear frequency modulation, the RMS error of the range measurement is determined by the following relation:

$$\sigma_r^2 = \frac{c}{2}\sigma_\tau^2 = \frac{c}{2}\left(1/\left(2q^2\Delta f\right)\right)^2, \qquad (24)$$

where σ_τ^2 is the error dispersion of the received signal delay time measurement relative to the sensed signal; q^2 is the signal-to-noise ratio by power; Δf is the frequency deviation of the frequency-modulated signal.

Availability of a priori information about the Doppler frequency and delay time reduces the errors of joint measurement of the range and radial velocity of SO and AO [31]. When using a sequence of frequency-modulated radio pulses, insufficient information about the Doppler frequency is obtained by measuring the delay time from pulse to pulse. In practice, in radars with both pulsed and continuous radiation, the frequency method is widely used to measure the range to SO and AO [32]. In pulsed radiation, the frequency method is implemented by processing a packet of radio pulses, the frequency of which varies from pulse to pulse according to a linear law:

$$f(t) = f_0 + \frac{\Delta f}{T_n}t, \qquad (25)$$

where f_0 is the carrier frequency; T_n is the radio pulse transmission interval.

The difference frequency is to be determined, which is related to the range r by the following expression:

$$F_p = 2\Delta f r / T_n c. \qquad (26)$$

Thus, according to (26), the range to the radar observed SO and AO can be determined by the following ratio:

$$r = \frac{cT_n}{2\Delta f}F_p. \qquad (27)$$

Therefore, an increase in the accuracy of joint measurement of the range and radial velocity of SO and AO radar-observed beyond the line-of-sight range can be ensured by using a sequence of broadband sensing signals with frequency modulation in radars.

In this case, the fluctuating errors of Doppler frequency measurement arising from the long-distance tropospheric propagation of the radar signal and its reflection conditions can be reduced several times by considering the fluctuations of the phase front of the radar signal wave in the algorithms of its time-frequency processing.

Conclusions

Therefore, with this rank, improving the information capabilities of coastal-based RS for surveillance of SO and AO in the sea area can be ensured as follows:

- using the features of the tropospheric propagation of radio waves with the possibility of its prediction over the sea surface by analysing the parameters of signals of automatic identification systems equipped with modern vessels in accordance with the International Convention for the Safety of Life at Sea.

- use of frequency modulation with large frequency deviation values in the sensing signals of radar detectors.

- application of optimal algorithms for measuring the range and radial velocity of the SO and AO, which include statistical characteristics of fluctuations of the phase front of the radar signal wave with frequency modulation.

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Пропозиції щодо підвищення інформаційних можливостей радіолокаційних станцій приморського базування щодо спостереження надводних та повітряних об'єктів

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Анотація. Радіолокаційні станції (РЛС) приморського базування широко використовуються для вирішення завдань щодо радіолокаційного спостереження надводних об'єктів (НО) та повітряних об'єктів (ПО). **Предметом** вивчення в статті є особливості врахування умов поширення радіохвиль для підвищення інформаційних можливостей РЛС приморського базування. **Метою статті** є дослідження можливостей щодо підвищення точності вимірювання дальності та радіальної швидкості НО та ПО, що спостерігаються за межами дальності прямої видимості РЛС приморського базування. **Завдання:** врахування флуктуацій фронту хвилі радіолокаційного сигналу, які виникають при його поширенні у хвилеводних шарах над морською поверхнею. Використані **методи:** метод найбільшої правдоподібності та частотний метод вимірювання дальності. Отримано наступні **результати**. Представлено результати експериментальних досліджень умов існування та параметрів тропосферних радіохвилеводів. Наведено порядок розрахунку енергетичних втрат при поширенні радіохвиль в прикордонному шарі атмосфери та визначено умови виявлення НО та ПО за межами дальності прямої видимості РЛС. Надано рекомендації щодо збільшення дальності виявлення НО та ПО, які пов'язані із можливістю існування тропосферних радіохвилеводів. Наведено пропозиції щодо оптимізації вимірювання радіальної швидкості НО та ПО з врахуванням статистичних характеристик флуктуацій фазового фронту хвилі радіолокаційного сигналу з частотною модуляцією, що забезпечує необхідну точність вимірювання дальності. **Висновки.** Розроблено пропозиції щодо збільшення дальності виявлення НО і ПО при хвилеводному поширенні радіохвиль над морською поверхнею та підвищення точності вимірювання їх радіальної швидкості та дальності. **Перспективним напрямком** подальших досліджень може бути визначення шляхів оптимізації вимірювання кутових координат в сучасних РЛС при хвилеводному поширенні радіохвиль над морською поверхнею.

Ключові слова: радіолокаційна станція; приморське базування; радіолокаційний сигнал; надводний об'єкт; повітряний об'єкт; тропосферний радіохвилевід; дальність; радіальна швидкість; фазові флуктуації; частотна модуляція.