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ASSESSING THE DETECTION ZONES OF RADAR STATIONS WITH THE ADDITIONAL USE OF RADIATION FROM EXTERNAL SOURCES

I. Ruban
Doctor of Technical Sciences, Professor, First Vice-Rector
Kharkiv National University of Radio Electronics
Nauky ave., 14, Kharkiv, Ukraine, 61166
H. Khudov
Doctor of Technical Sciences, Professor, Head of Department
Department of Radar Troops Tactic*
E-mail: 2345kh_hg@ukr.net
V. Lishchenko
Lecturer
Department of Armament of Radar Troops*
O. Pukhovyi
PhD, Head of Department**
S. Popov
PhD**
R. Kolos
PhD, Associate Professor, Deputy Head of Department
Department of Tactics of Combat (Operational) Support Units***
T. Kravets
PhD, Associate Professor, Lecturer
Department of Artillery Facility Complexes and Devices***
N. Shamrai
Head of the Group
Department of Tactics and Military Disciplines*
Yu. Solomonenko
PhD, Deputy Head of the Department
Department of Radar-Technical Troops of Anti-Aircraft*
I. Yuzova
PhD, Lecturer
Department of Information Technologies
Civil Aviation Institute
Klochkivska str., 228, Kharkiv, Ukraine, 61023
*Ivan Kozhedub Kharkiv National Air Force University
Sumska str., 77/79, Kharkiv, Ukraine, 61023
**Department of Radio-Technical and Special Troops
National Defense University of Ukraine named after Ivan Cherniakhovskyi
Povitroflotsky ave., 28, Kyiv, Ukraine, 03049
***Hetman Petro Sahaidachnyi National Army Academy
Heroiv Maidanu str., 32, Lviv, Ukraine, 79012

This paper reports the assessment of the detection zone of survey radar stations under a mode of single-place location. The detection zone under this mode significantly depends on the properties of the single-position effective surface of air objects scattering. The assessment of the detection zone of survey radar stations under a mode of the distributed location has been performed. It was established that the dimensions of the detection zone of air objects under a mode of the distributed location depend not only on the characteristics of the transmitting and receiving positions but on the system's geometry and the information combining technique as well. It was established that the size and nature of the detection zones of air objects under a mode of distributed reception depend on the distance to the base line and the degree of suppression of the penetrating signal in the receiving position. The detection zone of survey radar stations was estimated when the modes of single-position and distributed location merge. It was established that the shape of an air object detection zone depends on the design features of a particular air object and would take a different form for different types of air objects. However, the general trend to increase the size of the detection zone and reduce the dependence of its shape on the foreshortening of an air object when the merged modes of single-position and distributed reception is inherent in all types of air objects. The quality of using the merging of single-position and distributed reception modes at the predefined flight altitude of an air object was assessed. It was established that the application of the non-coherent combination of the single-position and distributed processing channels would increase the size of the detection zone of stealth aircraft objects by at least 30 % compared to the size of the single-position radar detection zone

***Keywords:** detection zone, single-position reception, distributed location, air object, radar station*

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1. Introduction

The practice of modern hostilities in Syria, Libya, eastern Ukraine, between Azerbaijan and Armenia, etc. shows the widespread use of stealth aircraft objects (AO) [1–3]. Employing unmanned aerial vehicles has become one of the main components of hostilities between Armenia and Azerbaijan [1]. Thus, some Western commentators have dubbed these activities the “South Caucasus war of unmanned aerial vehicles” [4].

Stealth aircraft are characterized by small effective surfaces of scattering, flights at medium, low, as well as extremely low altitudes, arching the terrain, etc. [5–7]. That greatly complicates the detection of AO by existing radar stations (RS).

The use of conventional methods to improve the quality of detection of stealth AO [8–11] leads to an increase in the quantity and energy potential of RS [12]. Modern three-coordinate RS that employ broadband phased signals, digital antenna arrays certainly solve the task of detecting stealth AO [3, 4, 13–15].

At the same time, the detection of stealth AO involves the survey two-coordinate RS with mechanical rotation in azimuth (the type of P-18MA (Ukraine), P-18MU (Ukraine), P-18 "Malahit" (Ukraine), etc.) [16, 17]. The authors of [18] proposed improving the quality of stealth AO detection by introducing an additional mode of distributed reception into an existing single-position survey RS. They improved the method of an AO detection by irradiating it from several transmitters, designed the scheme of an AO detector, and chosen the number of receiving channels to be merged. The study disregarded the issues related to the assessment of survey RS detection zones at additional radiation from external sources, which is a relevant task.

2. Literature review and problem statement

The use of advanced information technologies is proposed in works [19–22] to improve the quality of detection of stealth aircraft objects. The authors of [19] proposed conducting a sequentially parallel electronic survey of the detection zone based on the place angle, and a two-dimensional electronic scan of the antenna direction chart. However, such electronic scanning cannot be implemented by RS that mechanically surveys the airspace.

The authors of [20, 21] suggested using active, semi-active, and passive to transmit phased antenna arrays, and the digital synthesis of sensing signals with different parameters (carry frequency, type of modulation, bandwidth, duration, the frequency of pulse sending). [21] In addition, study [21] proposed applying the digital diagram formation of phased antenna arrays for the reception and automatic analysis of the interference situation involving the adaptive choice of tools and modes of protection against interference. That can be implemented only by RS with phased antenna arrays and an electronic survey of airspace.

Paper [22] suggested combining RS with secondary radar means, as well as increasing RS to an active-passive complex and using unconventional radar methods. That leads to a significant complication of the design of existing RS and the radar information processing methods.

The employment of new information technologies [19–22] proves effective when using modern new three-coordinated radars with phased antenna arrays. However, the use of such technologies by survey two-coordinate RS is almost impossible.

Papers [23, 24] proposed the following methods d to improve the effectiveness of detecting stealth AO:

– fuller utilization of the energy of the electromagnetic field, formed by the radiation from all sources of the signal reflected from AO, and the implementation of the modes of distributed reception;

– the use of the property of increasing the antenna amplification coefficient based on the principles of a distributed antenna array;

– the application of properties of a bistatic effective scattering surface (ESS) at distributed reception.

The methods reported in [23, 24] imply combining individual RS into a system and cannot be used when RS operates autonomously.

The methods of multi-position radar location and their practical use to improve the effectiveness of AO detection were considered in [25–27]. The peculiarities of multi-position radar systems involve the application of spatial-time methods of signal processing, which are received simultaneously at the spatially-distributed reception points. In this case, both active and passive reception methods are used. Paper [24] outlines the statistical theory of detection, determination of objects' coordinates, the definition of principles for the interposition identification of single measurements, and AO trajectories. The authors of [27] advanced the methods for combining radar information in multi-position radar systems. The application of multi-position radar methods improves the quality of AO detection. However, the cited papers [25–27] do not address the peculiarities of AO detection by the survey two-coordinate RS.

A significant contribution to the development of methods of combining radar information by multi-position radar systems was made by the authors of works [28, 29]. However, they did not solve the issue of coordinated operation of active single-position radars that rotate mechanically as part of a multi-radar system to improve the quality of detecting stealth AO.

The use of digital adaptive antenna systems based on phased antenna arrays is proposed in studies [30, 31] to improve the quality of AO detection. Such digital antenna arrays make it possible to build multi-beam receiving devices, as well as use broadband signals. General control over the digital adaptive antenna arrays is executed by a specialized computing system. Such systems have been termed "intelligent antennas". However, digital adaptive antenna arrays imply a complicated structure, specialized control procedure, and cannot be used in two-coordinate RSs that rotate mechanically.

Paper [18] proposed a method for detecting stealth AO by survey radars. The specified method implies a coordinated processing of accepted signals, a quadratic detection, the summation of detector outputs based on weight. The operations described above are carried out in each processing channel, in each element that corresponds to the appropriate separate volume and the corresponding separate Doppler frequency [18].

The authors of [18] proved that it is advisable to have two channels of reception within a survey RS – a single-position reception channel and a channel of distributed reception (Fig. 1).

In Fig. 1, the following designations are used [18]: Dt is the detector, Q_1, Q_2 are the weight factors, t_{12} is the signal delay time, which is due to different distances between the receiving and transmitting positions.

However, the authors of [18] disregarded the assessment of an important tactical-technical characteristic – the zones of detection by survey RS at the additional use of radiation from external sources.

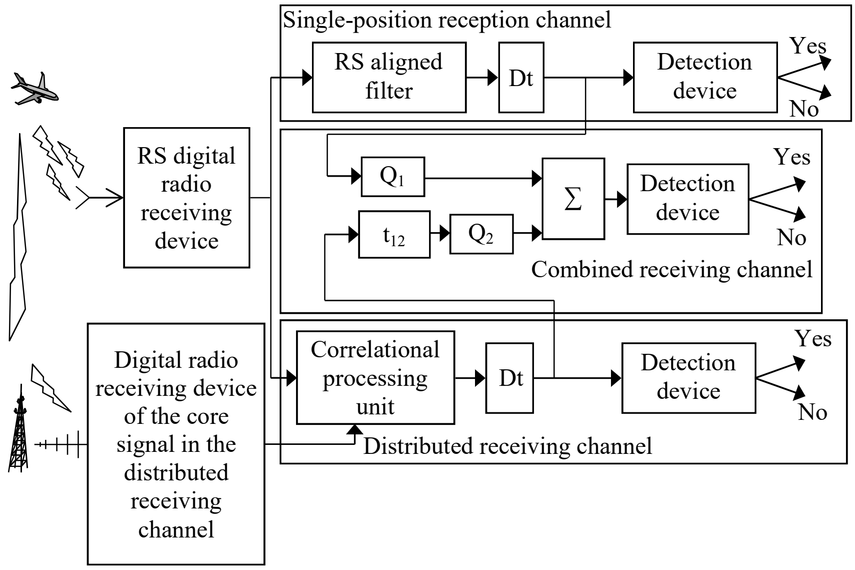

Fig. 1. Channels for receiving and processing of echo signals in a survey RS when merging the single-position and distributed reception [18]

3. The aim and objectives of the study

The aim of this study is to estimate the detection zones by survey RS involving the additional use of radiation from external sources, and to compare radar detection zones at the single-position and distributed signal reception, as well as at merging the single-position and distributed signal reception.

To accomplish the aim, the following tasks have been set:

– to investigate the characteristics of the detection zone by survey RS under a mode of single-position location;

– to examine the characteristics of the detection zone by survey RS under a mode of the distributed location;

– to investigate the characteristics of the detection zone by survey RS when merging the single-position and distributed location modes;

– to estimate the quality of application of the combination of single-position and distributed reception modes at the predefined flight altitude of an aircraft object.

4. Assessment of survey RS detection zones involving the additional use of radiation from external sources

The following limitations and assumptions were adopted during our study:

– we consider the two-coordinate radars that rotate mechanically (such radars are most often used by radio technical troops). The tactical-technical characteristics of RS are given below in the calculations;

– the number of receiving channels is two – the main (single-position receiving channel) and additional (a channel of distributed reception) receiving channels;

– the type of interference components in an input signal is not taken into consideration;

– a direct signal from an external radiation source does not affect the main receiving channel (single-position receiving channel) in a survey RS;

– the operational synchronization of the main and additional receiving channels in survey radars is ensured;

– the AO considered are the stealth objects (such as a cruise missile, an unmanned aerial vehicle). The effective scattering surfaces (ESS) of the specified AO are given below in the calculations.

4. 1. Assessment of the detection zone of survey RS under a single-position location mode

The dimensions of a survey RS detection zone under a mode of single-position location are determined from the radar equation, taking into consideration the features of the terrain, the features of radio wave propagation, and the reflecting properties of AO. The AO detection quality indicators are defined by a signal/noise ratio at the input of the detection device after the appropriate coordinated processing of received echo signals. The output of the unit for the coordinated processing of received echo signals generates a value, which is proportional to the energy of the received signal and is determined from the following expression (1):

$$E_{ao}=\frac{P_i\tau_i N_k G^2\lambda^2\sigma_{ao}}{R_{ao}^4(4\pi)^3 10^{0,1L}}, \qquad (1)$$

where E_{ao} is the energy of the signal received from AO; R_{ao} is the range to the aircraft object (AO); P_i is the pulse power; τ_i is the duration of the sensing pulse; N_k is the number of coherent accumulated pulses; G is the amplification coefficient of the receiving-transmitting antenna; σ_{ao} is the AO ESS; λ is the wavelength of the sensing signal; L, dB is the additional losses in the RS equipment.

The maximum number of pulses that can be used to detect an AO depends on the speed of space survey, the antenna pattern width (APW), and is determined from the following expression (2):

$$N_{ao}=\frac{t_{obz}\beta_{0,5P}}{360T_p}, \qquad (2)$$

where N_{ao} is the number of pulses reflected from AO; t_{obz} is the time of circular survey of space; $\beta_{0.5P}$ is the PWA for azimuth; T_p is the period of repeated probing pulses.

When detecting AO against the background of the natural noise from a receiving device, the signal/noise ratio at the output from the coordinated signal processing unit is determined from the following expression (3):

$$q^2=\frac{2E_{ao}}{N_0}=\frac{2E_{ao}}{kT_0K_n}, \qquad (3)$$

where q^2 is the signal/noise ratio for power at the output from the coordinated signal processing unit; N_0 is the spectral density of the natural noise from a receiving device; k=1.38·10^{-23} J/K is the Boltzmann constant; T_0=300 K is the standard temperature; K_n is the noise factor of the receiving device.

The geometric location of points with the same value of the received signal energy from AO (E_{ao}), which ensures the same signal/noise ratio (q^2) value, would determine the corresponding detection zone of a particular AO with the appropriate detection quality indicators.

We shall calculate the detection zone of a survey RS under a single-position location mode. In the calculations, and hereafter, an RS to consider is the pulse RS, the type of P-18 "Malahit", with the following tactical-technical characteristics [16, 17]: a meter range; two-coordinate; pulse power of the sensing signal, 6.5 kW; circular space survey time, t_{obz}=10 s; APW for azimuth, $\beta_{0.5P}$=6°; the period of repeated sensing pulses, T_p=2.5 ms; the maximum number of accumulated pulses, to 70; amplitude modulation; antenna type, an antenna array that rotates mechanically.

An AO to consider is the AGM-86C cruise missile (USA). The ESS of the cruise missile AGM-86C is based on the calculations given in Table 1 [32–34].

Table 1

The ESS value of AGM–86C cruise missile [32–34]

ESS type	Polarization	Value, m²		
		azimuthal angle, degree		
		0...45	45...135	135...180
Medium	Horizontal	11.342	10.454	10.603
	Vertical	2.609	4.894	3.024

Table 1 demonstrates that the value of AO ESS changes depending on the foreshortening of AO relative to the radar, which leads to appropriate changes in the detection zone. The example of a change in the detection zone of AO of a cruise missile the type of AGM-86C (USA) when it changes its angle is shown in Fig. 2.

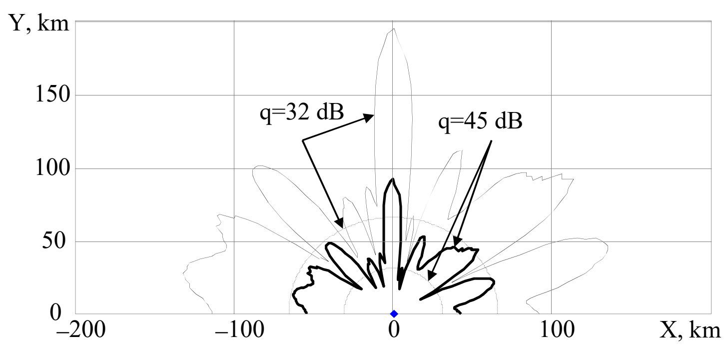

Fig. 2. Example of a change in the shape of the detection zone of AO of a cruise missile the type of AGM-86C by a single-position RS dependent on a change in the ESS value when changing the foreshortening of AO

In Fig. 2, a dotted line shows a detection zone at the constant AO ESS value, which ensures a threshold signal/noise ratio of 32 dB and 45 dB. A solid line indicates a detection zone for a cruise missile of the AGM-86C type at a threshold signal/noise ratio of 32 dB and 45 dB.

The analysis of Fig. 2 demonstrates that the properties of a single-position AO ESS can lead to significant changes in the shape of the detection zone by a single-position RS when changing the foreshortening of AO relative to the RS. Thus, the detection zone of stealth AO under a single-position location mode significantly depends on the AO foreshortening.

4. 2. Assessment of the detection zone of survey RS under a mode of the distributed location

The dimensions of the detection zone under a mode of the distributed location depend, in addition to the terrain, on the peculiarities of radio wave propagation, the reflective properties of AO, as well as the geometry of the system. The geometry of the system denotes the number and spatial location of receiving and transmitting positions and the way information is combined.

The characteristics of the detection zone of a distributed RS may vary depending on the predefined operating modes. Under a mode of survey and search for AO, a decision on the presence of AO can be taken when detecting an echo signal in at least one of several receiving positions. When accompanying an AO and accurately determining its coordinates and a speed vector, simultaneous detection in several receiving positions is required. It is clear that the range of a distributed RS under a survey and search mode is larger and the detection zone is wider than that under a mode of accompanying and accurate measurement of coordinates and speed [18, 25].

To determine the range of AO detection by a distributed RS, we use a value that is derived at the output from a unit of coordinated processing of the accepted signal and which defines the energy of the accepted signal under a mode of the distributed location, from the following expression (4):

$$E_R = \frac{P_T t_n G_T G_R \lambda^2 \sigma_b}{(4\pi)^3 R_T^2 R_R^2 \gamma_{ap} \gamma_{pp}}, \qquad (4)$$

where P_T is the transmitter signal strength; E_R is the energy of the received echo signal in the receiving position; t_n is the time of coherent accumulation of the accepted signal in a unit of coordinated processing; G_T, G_R are the amplification coefficients of antennas in the transmission and receiving positions, respectively; σ_b is the bistatic AO ESS; R_T, R_R is the range between an AO and the transmitting and receiving position, respectively; γ_{pp} is the energy loss when a signal propagates from the transmission position to AO and from AO to the receiving position; γ_{ap} is the loss in the equipment of the transmitting and receiving positions (γ_{pp}>1, γ_{ap}>1).

The difference of a similar equation for a single-position RS is that it, instead of the range from RS to AO of the fourth power R_{ao}^4, includes the product of the squares of ranges from the receiving and transmitting positions $R_T^2 R_R^2$. A single-position AO ESS is replaced with a bistatic ESS whose value changes when changing the bistatic angle. The remaining quantities are the same as for a single-position RS with separate transmitting and receiving positions although the values of these quantities for the single-position and distributed RS may vary.

When detecting AO against the background noise of the receiving device, the signal/noise ratio at the output from the unit of coordinated signal processing is determined from expression (3), which, taking into consideration (4), takes the following form (5):

$$q_p^2 = \frac{2E_R}{N_0} = \frac{2E_R}{kT_0 K_{nr}} = \frac{2P_T t_n G_T G_R \lambda^2 \sigma_b}{(4\pi)^3 R_T^2 R_R^2 \gamma_{ap} \gamma_{pp} k T_0 K_{nr}}, \qquad (5)$$

where q_p^2 is the signal/noise ratio for the power at the output from a device of coordinated processing of echo signals in the channel of distributed reception; N_0 is the spectral density of the natural noises in a receiving device; $k=1.38\cdot10^{-23}$ J/K is the Boltzmann constant; $T_0=300$ K is the standard temperature; K_{nr} is the noise factor of the receiving device in the channel of distributed reception.

Expressions (4), (5) make it possible to build an RS detection zone under a mode of distributed reception as a geometric place of points with the same value of the received energies of signals from AO (E_R), which ensures the same value of the signal/noise ratio $\left(q_p^2\right)$. The quality indicators of AO detection at a certain value of the signal/noise ratio would depend on the nature of the received signals' fluctuation.

Provided AO ESS (σ_b) and the parameters of the receiving and transmitting equipment do not change, a boundary of the detection zone of a distributed RS would be described by Cassini ovals for the fixed values of the product of distances $R_T^2 R_R^2$ [35]. This statement holds for the case of the existence of two receiving channels – main and additional. This particular case is considered in this work. With the increase in the number of additional receiving channels, a boundary of the detection zone by such a system would be described not by Cassini ovals but by the figures of complex irregular shapes [35]. The shape of Cassini ovals depends on the correlation between the product of the ranges $R_T^2 R_R^2$ to AO and the base L between the transmitting and receiving positions – expression (6):

$$\frac{R_T^2 R_R^2}{(0.5L)^2}=C^2, \qquad (6)$$

where C^2 is the constant coefficient; L is the base length (a distance between the transmitting and receiving positions).

When locating the receiving and transmitting position along the abscissa axis at points whose coordinates are $x=-1$; $x=1$; the equations of Cassini ovals in the cartesian coordinate system are determined from the following expression (7):

$$\left(x^2+y^2+1\right)^2-4x^2=C^2, \qquad (7)$$

where C^2 is a constant coefficient defined from expres-sion (6).

Depending on the AO position relative to the base line of a distributed RS, a value of the AO bistatic angle changes, which leads to changes in its bistatic ESS. This causes appropriate changes in the detection zone. In our calculations, a value of the bistatic ESS of the cruise missile AGM-86C would be taken in accordance with the data given in Table 2 [32–34].

Table 2

AGM–86C cruise missile's bistatic ESS value [32–34]

ESS type	Polarization	Value		
		spread angle, degree		
		0…45	45…135	135…180
medium ESS	Horizontal	3.974	1.262	19.99
	Vertical	2.818	2.636	7.061

The example of a change in the AO detection zone when changing a bistatic angle is shown in Fig. 3.

Fig. 3, *a* shows the AO detection zones for a bistatic RS, which are limited to the lines of the equal value of a signal/noise ratio, provided the AO ESS value does not depend on a bistatic angle. Fig. 3, *b* demonstrates the AO detection zones similar to those in Fig. 3, *a* but taking into consideration the dependence of AO ESS values on a bistatic angle. The dependence of ESS on a bistatic angle corresponds to the dependence inherent in the AO of a cruise missile the type of AGM-86C (USA).

When comparing the detection zones in Fig. 3, *a, b*, one may see that at long distances from the base line, when the changes in a bistatic angle are negligible, the ESS value remains almost constant. At the same time, at short distances from the base line, there are significant changes in the shape of a detection zone.

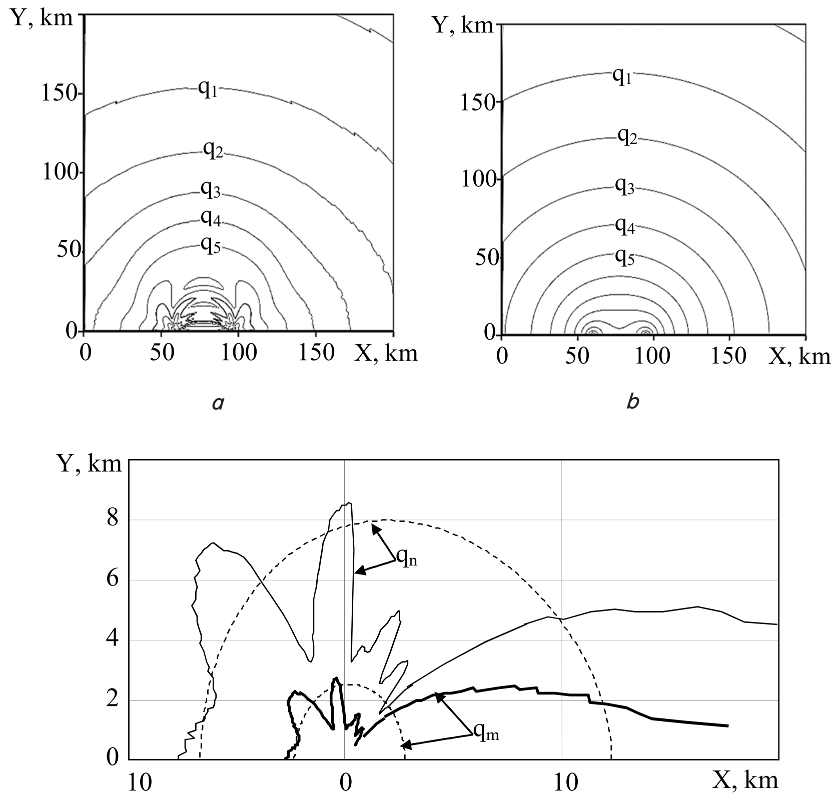

Fig. 3. Example of a change in the shape of AO detection zone of a cruise missile the type of AGM-86C by the distributed RS by changing the value of the bistatic AO ESS when changing the bistatic angle: *a* – at a constant ESS value of the reference AO ($q_1<q_2<q_3$...); *b* – the ESS value of an actual AO, which depends on a bistatic angle ($q_1<q_2<q_3$...); *c* – overlaying the zones of detection of the reference and actual AO ($q_n<q_m$)

Fig. 3, *c* shows the overlay of AO detection zones with the ESS that does not depend on the values of a bistatic angle, and the AO ESS of a cruise missile the type of AGM-86C, which are located near the base line. Fig. 3, *c* shows that changing the bistatic angle could significantly affect the size of the detection zone of stealth AO by RS with the distributed mode of location.

One of the features of using the distributed mode for detecting AO location is the existence of a penetrating signal from the radiation source. Consequently, AO detection is carried out against the background of a mixture of natural noises and the penetrating signal. To reduce the level of a penetrating signal at the input to a threshold device, special measures are taken for the receiving device (reducing the level of APW lateral petals, special units that compensate for the penetrating signal, etc.). Taking into consideration the effect of a penetrating signal, expression (5) takes the following form (8):

$$q_{rp}^2 = \frac{E_R}{0.5N_0 + K_{rp}N_p} = \frac{P_T t_n G_T G_R \lambda^2 \sigma_b}{(4\pi)^3 R_T^2 R_R^2 \gamma_{ap}\gamma_{pp}\left(\frac{kT_0K_n}{2} + K_{rp}P_p t_n\right)}, \quad (8)$$

where q_{rp}^2 is the signal/noise ratio for the power at the output from a unit of coordinated processing of signals from a distributed channel, taking into consideration the effect of a penetrating signal; K_{rp} is the coefficient of suppression of the penetrating signal in a spatial-time processing system; N_p is the spectral density of the penetrating signal at the output from a unit of coordinated filtration without the use of suppression systems; P_p is the power of the penetrating signal at the input to the unit of coordinated filtration without taking into consideration the effect of the penetrating signal suppression systems.

The power of the penetrating signal at the input to the unit of coordinated signal processing without taking into consideration the effect of suppression systems P_p is determined from the following expression (9):

$$P_p = \frac{P_T G_T G_R \lambda_p^2}{(4\pi)^2 L^2} F_T\left(\varepsilon_{pr}, \beta_{pr}\right) F_R\left(\varepsilon_{per}, \beta_{per}\right), \quad (9)$$

where P_T is the signal strength at the transmitter output; G_T, G_R G_T, G_R are the amplification coefficients of antennas in the transmitting and receiving positions, respectively; λ_p is the wavelength of the penetrating signal; L is the distance between the transmitting and receiving positions (base length); $F_T(\varepsilon_{pr}, \beta_{pr})$, $F_R(\varepsilon_{per}, \beta_{per})$ are the normalized APW of the transmitting and receiving positions, respectively; ε_{pr}, β_{pr} is the angle of place and the azimuth of the receiving position relative to the transmitting position; ε_{per}, β_{per} is the angle of place and the azimuth of the transmitting position relative to the receiving position.

The existence of a penetrating signal leads to a change in the shape of an AO detection zone by the distributed system. The example of a change in the AO detection zone under the action of the penetrating signal is shown in Fig. 4.

Fig. 4, *a* shows the changes in an AO detection zone (the lines of the equal value of the signal/noise ratio) whose ESS does not depend on a bistatic angle. Fig. 4, *b* shows the changes in an AO detection zone taking into consideration the ESS dependence on a bistatic angle. The comparison of Fig, 3, *a*, *b*, and Fig. 4, *a*, *b* demonstrates that the influence of the penetrating signal leads to a decrease in the size and an increase in the cutting of the detection zone. A particularly strong influence of the penetrating signal on the nature of changes in the detection zone is observed near the base line for stealth AO whose ESS values depend on a bistatic angle.

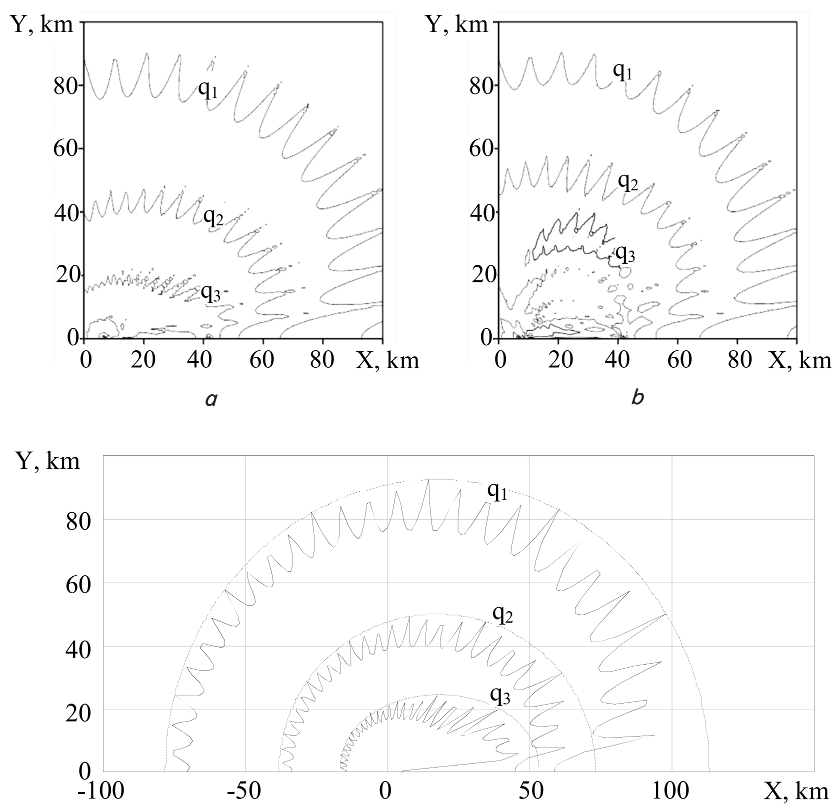

Fig. 4. Example of a change in the shape of a zone for detecting AO of a cruise missile the type of AGM-86C by the distributed RS under the action of the penetrating signal from a transmitter: *a* — at a constant AO ESS value ($q_1 < q_2 < q_3$); *b* — when changing the ESS value of an actual AO due to a bistatic angle ($q_1 < q_2 < q_3$); *c* — overlaying the AO detection zones at constant ESS taking into consideration (solid line) and excluding (dotted line) the effect of the penetrating signal ($q_1 < q_2 < q_3$)

Fig. 4, *c* shows the overlaying of AO detection zones when taking into consideration (solid line) and excluding (dotted line) the effect of a penetrating signal for AO whose ESS does not depend on a bistatic angle. Fig. 4, *c* demonstrates that the impact of the penetrating signal leads to a sharp reduction in the size of the detection zone along the direction towards a transmitting position for the case when AO ESS does not depend on a bistatic angle. Consequently, special measures should be taken to reduce the impact of a penetrating signal on the size of a detection zone.

Thus, the size and nature of the AO detection zones under a distributed reception mode depends on the distance to the base line (the closer AO to the base line, the greater the impact of the dependence of an ESS value on a bistatic angle) and the degree of suppression of the penetrating signal in the receiving position.

4. 3. Assessing a detection zone of survey RS when merging the single-position and distributed location modes

It is known from [18] that it is advisable to combine the single-position and distributed location modes through the non-coherent summing of the results of coordinated signal processing in the respective channels after appropriate compensation for time delays and frequency offsets of signals in channels.

Taking into consideration expression (4), after the weight-based summation of the results from coordinated signal processing in the channels of the single-position and distributed locations, the quantities that are predetermined by the presence of usable signal and noise are calculated from expressions (10) to (12):

$$E_{\Sigma}=\frac{E_{ao}}{N_{0o}}+\frac{E_R}{N_{0p}}=$$
$$=\frac{P_i\tau_i N_k G^2\lambda^2\sigma_{ao}}{(4\pi)^3 N_{0o}R_{ao}^4 10^{0,1L}}+\frac{P_T t_n G_T G_R\lambda^2\sigma_b}{(4\pi)^3 N_{0p}R_T^2 R_R^2\gamma_{ap}\gamma_{pp}}, \qquad (10)$$

$$N_{\Sigma}=\sqrt{\left(\frac{N_{0o}}{N_{0o}}\right)^2+\left(\frac{N_{0p}}{N_{0p}}\right)^2}=\sqrt{2}, \qquad (11)$$

$$N_{0o}=kT_0K_n,\quad N_{0p}=kT_0K_{nr}+K_{pp}, \qquad (12)$$

where E_{Σ} is the value of the output quantity after weight-based summation, which is due to the presence of a usable signal; E_{ao}, E_R are the values of the output quantities due to a usable signal, at the outputs from the single-position and distributed receiving channels, respectively; N_{Σ} is the value of the output quantity after weight-based summation, which is due to the presence of noises and interference in the channels; N_{0o}, N_{0p} are the spectral densities of noises and interferences in the single-position and distributed receiving channels, respectively; N_p is the spectral density of a penetrating signal at the output from a unit of coordinated filtration without the use of compensation systems; K_{pp} is the coefficient of suppression of a penetrating signal in the spatial-time processing system.

Taking into consideration expressions (10) and (11), it is possible to estimate a minimum value of the signal/noise ratio that can be derived after the non-coherent summation of signal processing results in the single-position and distributed receiving channels in the form of expression (13):

$$q_{\Sigma}^2=\frac{E_{\Sigma}}{N_{\Sigma}}=\frac{1}{\sqrt{2}}\left(\frac{E_{ao}}{N_{0o}}+\frac{E_R}{N_{0p}}\right). \qquad (13)$$

The geometric location of points with the same signal/noise ratio value $\left(q_{\Sigma}^2\right)$, would determine the corresponding AO detection zone of a certain type with appropriate detection quality indicators. Depending on the AO foreshortening relative to the position of receiving and transmitting positions, the value of the monostatic and bistatic ESS changes, which leads to the appropriate changes in the detection zone under the single-position and distributed modes. The example of a change in the detection zone of stealth AO of a cruise missile the type of AGM-86C when merging the single-position and distributed reception modes is shown in Fig. 5, 6.

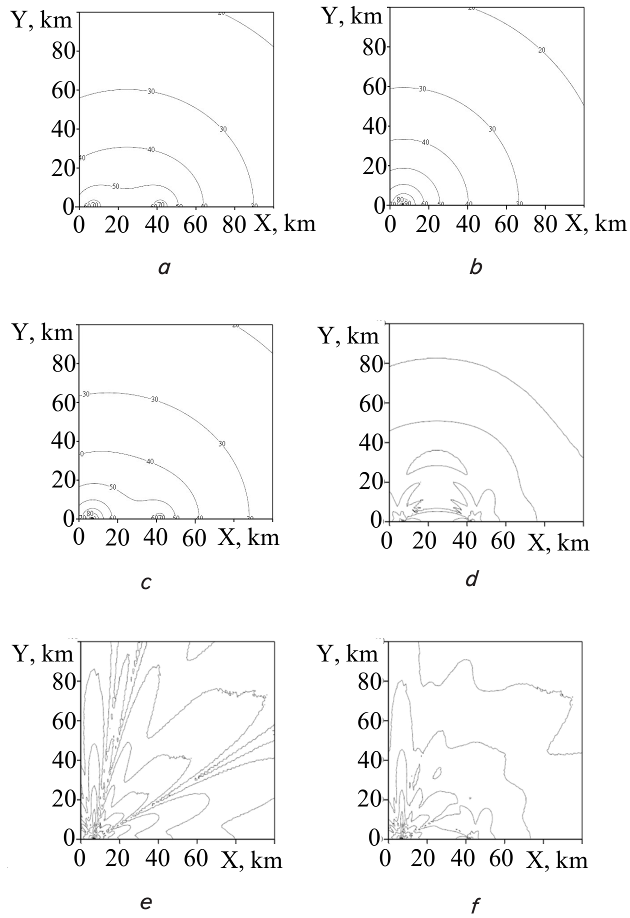

Fig. 5. Example of change in the shape of an AO detection zone of a cruise missile the type of AGM-86C without taking into consideration the effect of the penetrating signal: *a* – the mode of distributed reception at a constant AO ESS value; *b* – the mode of single-position reception at a constant AO ESS value; *c* – combining the modes of single-position and distributed reception at a constant AO ESS value; *d* – the mode of distributed reception taking into consideration the dependence of ESS value on a bistatic angle; *e* – a single-position reception mode taking into consideration the dependence of ESS value on the AO foreshortening; *f* – combining the modes of single-position and distributed reception taking into consideration the dependence of ESS value on a bistatic angle and the AO foreshortening

The example of overlaying the detection zones of different-type AO taking into consideration the effect of the penetrating signal for the modes of distributed and single-position reception and when they are combined is shown in Fig. 7.

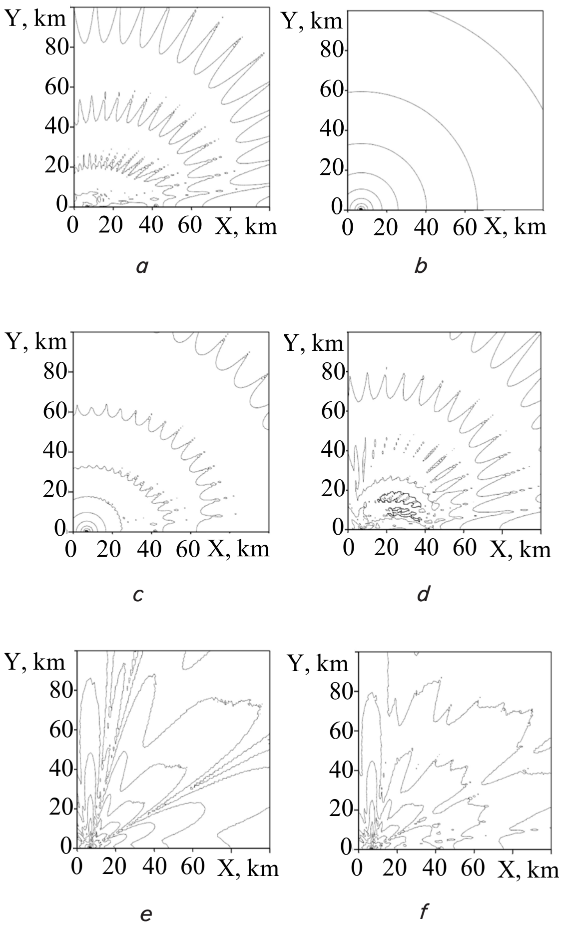

Fig. 6. Example of change in the shape of an AO detection zone of a cruise missile the type of AGM-86C taking into consideration the effect of the penetrating signal: *a* — the mode of distributed reception at a constant AO ESS value; *b* — the mode of single-position reception at a constant AO ESS value; *c* — combining the modes of single-position and distributed reception at a constant AO ESS value; *d* — the mode of distributed reception taking into consideration the dependence of ESS value on a bistatic angle; *e* — a single-position reception mode taking into consideration the dependence of ESS value on the AO foreshortening; *f* — combining the modes of single-position and distributed reception taking into consideration the dependence of ESS value on a bistatic angle and the AO foreshortening

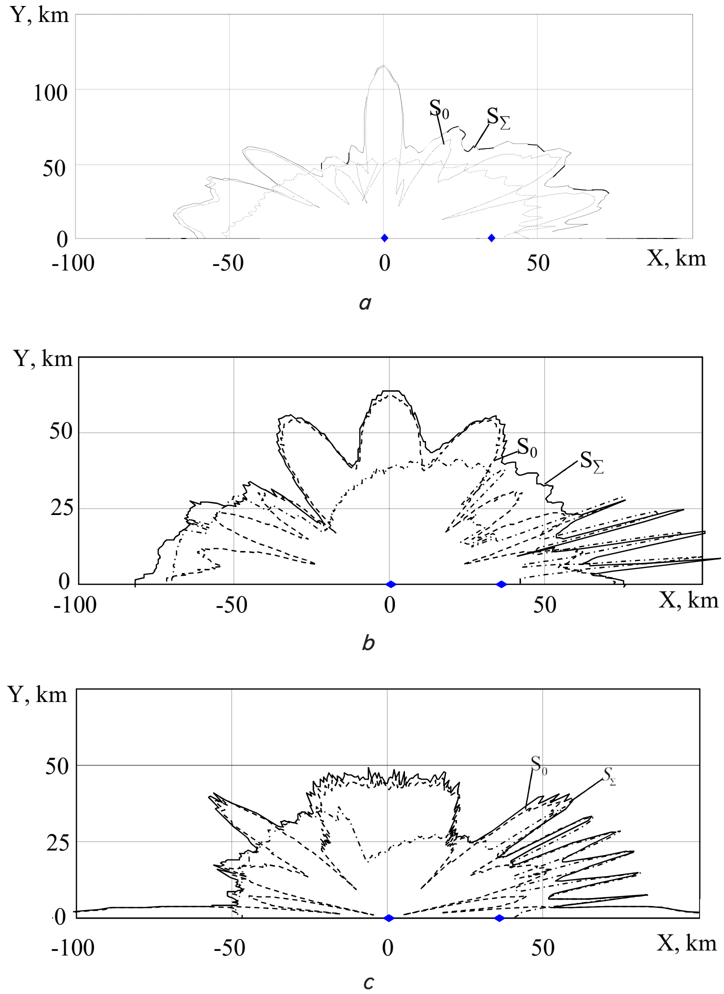

Fig. 7. Example of overlaying detection zones taking into consideration the effect of the penetrating signal for the distributed (bar-dotted line), single-position (dotted line), and the combined modes (solid line), S_0, S_Σ — the overlapping area of detection zones under the single-position and combined modes: *a* — AO the type of cruise missile AGM-86C; *b* — AO the type of Taurus KEPD 350 cruise missile (USA); *c* — AO the type of unmanned aircraft Tu-143 "Reis" (Ukraine)

Fig. 5, *a–c* shows that at a constant ESS value (not dependent on the AO foreshortening) merging the single-position mode (Fig. 5, *b*) and the distributed (Fig. 5, *a*) receiving modes provides for a slight increase in the detection zone (Fig. 5, *c*). Fig. 5, *d, e* demonstrates that when taking into consideration the dependence of an ESS value on the AO foreshortening the merging of the single-position (Fig. 5, *d*) and the distributed (Fig. 5, *d*) receiving modes can provide for a significant improvement in the shape of the detection zone (Fig. 5, *f*) by reducing the spread of ESS values when changing the AO foreshortening.

Fig. 6, *a* shows that the influence of the penetrating signal distorts the shape of the detection zone under a mode of distributed reception at a constant ESS value. This leads to a deterioration in the detection zone when combining the single-position and distributed receiving modes (Fig. 6, *c*). Fig. 6, *d, e* demonstrates that when taking into consideration the influence of the penetrating signal and accounting for the dependence of ESS value on the AO foreshortening merging the single-position (Fig. 6, *e*) and the distributed receiving modes (Fig. 6, *d*) can ensure an improvement in the detection zone (Fig. 6, *f*). At the same time, the comparison of Fig. 5, *f* and Fig. 6, *f* shows that the influence of the penetrating signal reduces the effectiveness of combining the modes of single-position and distributed reception. Consequently, in the practical implementation of the distributed receiving regime, it is necessary to ensure the suppression of the penetrating signal. This affects the effectiveness of the practical implementation of the combination of the single-position and distributed receiving modes.

Fig. 7, *a–c* shows that for the stealth AO of the above types the detection zone when combining the modes of single-position and distributed reception is increased, and its shape becomes less dependent on the AO foreshortening. It should be noted that the shape of an AO detection zone depends on the design features of a particular AO and would take a different form for different types of AO. However, a general trend to increase the size of the detection zone and reduce the dependence of its shape on the AO foreshortening when merging the modes of single-position and distributed reception would be inherent in all types of AO.

5. Assessing the quality of applying the merging of single-position and distributed receiving modes at the predefined flight altitude of an air object

To quantify the quality of applying the merging of single-position and distributed receiving modes at the predefined altitude, it is advisable to use the ratio of the overlapping areas of the detection zone at this altitude (expression (14)):

$$K_{H_k,m}=\frac{S_\Sigma\left(H_k,m\right)}{S_0\left(H_k,m\right)}, \tag{14}$$

where $K_{H_k,m}$ is the quality indicator of applying the merging of single-position and distributed receiving modes for detecting the m-type AO at the flight altitude H_k, m=1...M; $S_\Sigma(H_k, m)$ is the overlapping area of the m-type AO detection zone at altitude H_k, when merging the single-position and distributed receiving modes; $S_0(H_k, m)$ is the overlapping area of the m- type AO detection zone at altitude H_k, when using a single-position mode (RS standard operation); H_k is the altitude of the k-th section of a detection zone, k=1...K; K is the number of intersections being analyzed; M is the number of AO types being analyzed.

To quantify the generalized quality of using the merging of single-position and distributed receiving modes throughout the detection zone, it is advisable to use a generalized indicator (expression (15)):

$$K_\Sigma=\frac{1}{KM}\sum_{m=1}^{M}\sum_{k=1}^{K}K_{H_k,m}, \tag{15}$$

where K_Σ is the generalized quality indicator of applying the merging of single-position and distributed receiving modes to detect the M types of AO in a specified survey area.

For the AO whose detection zone examples are shown in Fig. 7, the quality indicators of applying the merging of single-position and distributed receiving regimes (14) are given in Table 3.

Table 3

Quality indicators when merging the single-position and distributed location modes

No. of entry	AO type	S_Σ/S_0	K_Σ
1	Cruise missile AGM–86C	1.37	1.33
2	Cruise missile Taurus KEPD 350	1.32	
3	Unmanned aircraft Tu–143 «Reis»	1.29	

The analysis of Table 3 reveals that the use of the non-coherent merging of single-position and distributed processing channels can provide for an increase in the size of a zone for detecting stealth AO compared to the size of a single-position RS detection zone.

For example, for AO the type of cruise missile AGM-86C, the ratio S_Σ/S_0 is 1.37 (according to Table 3). This means that by merging the single-position and distributed processing channels, a zone of detecting this type of AO has increased by 37 % compared to the single-position location.

For example, for AO the type of cruise missile Taurus KEPD 350, the S_Σ/S_0 ratio is 1.32 (according to Table 3). This means that merging the single-position and distributed processing channels has increased the detection zone of this type of AO by 32 % compared to the single-position location.

For example, for AO the type of unmanned aircraft Tu-143 “Reis”, the S_Σ/S_0 ratio is 1.29 (according to Table 3). This means that merging the single-position and distributed processing channels has increased the detection zone of this type of AO by 29 % compared to the single-position location.

On average, for the specified types of AO, the merging of single-position and distributed processing channels has increased the detection zone of this type of AO by (1.37+1.32+1.29)/3=1.33, that is, by 33 % compared to the single-position location.

Thus, the analysis of Table 3 reveals that the use of the non-coherent merging of single-position and distributed processing channels can provide for an increase in the size of the detection zone of stealth AO by at least 30 % on average, compared to the size of the single-position RS detection zone. The increase is explained by the merging of the single-position and distributed processing channels.

Thus, combining the modes of distributed and single-position reception can provide for an increase in the size of the AO detection zone by 30 % or more, and reduce the dependence of its shape on the AO foreshortening. For each type of AO, the quality of the application of the proposed method would be different. It is advisable to use, as a quality indicator, the ratio of the overlapping area of a detection zone at the predefined AO flight altitude, provided by the application of the proposed method, to the cross-sectional area of the detection zone, which is provided by a single-position RS. It is advisable to use the average value of indicators for the types of AO and flight altitudes as a generalized quality indicator of using the proposed method.

6. Discussion of the study results on assessing the detection zones of survey radar stations with the additional use of radiation from external sources

We have assessed the detection zone of survey RS under a mode of single-position location. It was established that the properties of a single-position AO ESS can lead to significant changes in the shape of the detection zone by a single-position RS when changing the foreshortening of AO relative to the RS.

We have assessed the detection zone of survey RS under a mode of the distributed location. It was established that the dimensions of an AO detection zone under a mode of the distributed location depend not only on the characteristics of the transmitting and receiving positions but also on the geometry of the system and the technique of combining information. Thus, the range of the distributed RS under a mode of survey and search is greater, and the detection zone is wider, than those under a mode of survey and accurate measurement of coordinates and speed. The difference between the equation of the range of AO detection by a distributed RS, expression (4), and a similar equation for the single-position RS is that it includes, instead of the distance between RS and AO of the fourth power, the product of the squares of distances between the receiving and transmitting positions $R_T^2 R_R^2$. In addition, unlike a single-position AO ESS, the value of a bistatic AO ESS changes when a bistatic angle changes. The comparison of detection zones in Fig 3, *a*, *b* demonstrates that at long distances from the base line, when the changes in a bistatic angle are negligible, the ESS values remain almost constant. At the same time, at short distances from the base line, there are significant changes in the shape of a zone for detecting AO. Our analysis of Fig. 3 reveals that changing a bistatic angle can significantly affect the size of the detection zone of stealth AO by RS with a distributed mode of location.

It was established that one of the features in using the distributed mode of AO location is the existence of a penetrating signal from the source of radiation. The presence of a penetrating signal leads to a change in the shape of an AO detection zone by the distributed system (Fig. 4). It was found that a particularly strong influence of the penetrating signal on the nature of changes in the detection zone is observed near the base line for stealth AO whose ESS value depends on a bistatic angle. Fig. 4. *c* demonstrates that the impact of the penetrating signal leads to a sharp reduction in the size of the detection zone in the direction towards a transmitting position for the case when AO ESS does not depend on a bistatic angle. Consequently, special measures should be taken to reduce the impact of the penetrating signal on the size of the detection zone.

We have assessed the detection zone of survey RS when merging the single-position and distributed location modes. It was established that depending on the AO foreshortening relative to the location of the receiving and transmitting positions, a value of the monostatic and bistatic ESS changes, which leads to appropriate changes in the detection zone under the single-position and distributed modes (Fig. 5, 6). The example of overlaying the detection zones of AO of different types taking into consideration the effect of the penetrating signal for the modes of distributed and single-position reception and when they are combined is shown in Fig. 7. It was established that the practical implementation of the mode of distributed reception requires that the suppression of the penetrating signal should be provided. Our analysis of Fig. 7, *a*–*c* reveals that for stealth AO the detection zone when merging the single-position and distributed receiving modes increases and its shape becomes less dependent on the AO foreshortening. The shape of an AO detection zone depends on the design features of a particular AO and would take a different form for different types of AO. However, the general tendency to increase the size of the detection zone and reduce the dependence of its shape on the AO foreshortening when merging the single-position and distributed receiving modes would be inherent in all types of AO.

We have assessed the quality of applying the merging of single-position and distributed receiving modes at the predefined AO flight altitude. To quantify the quality of application of merging the single-position and distributed reception modes at the predefined altitude, the ratio of the cross-sectional areas of the detection zone at this altitude is used; expression (14). A generalized indicator (expression (15)) is applied to quantify the generalized effectiveness of the use of the combined single-position and distributed receiving modes throughout the detection zone. Table 3 gives the quality indicators when combining the single-position and distributed location modes for some types of AO. Our analysis of Table 3 reveals that the use of the non-coherent merging of the single-position and distributed processing channels can provide for an increase in the size of the detection zone of stealth AO by at least 30 % compared to the size of a single-position RS detection zone.

Thus, combining the modes of the distributed and single-position reception can provide for an increase in the size of an AO detection zone by 30 % or more, and reduce the dependence of its shape on the AO foreshortening. For each type of AO, the effectiveness of the proposed method would be different. It is advisable to use, as a quality indicator, the ratio of the cross-sectional area of the detection zone at the predefined AO flight height, provided by the application of the proposed method, to the cross-sectional area of the detection zone, which is provided by a single-position RS. As a generalized quality indicator of using the proposed method, it is advisable to apply the average value of indicators for the types of AO and flight altitudes.

The following limitations and assumptions are inherent in this study: the survey two-coordinate RS that rotate mechanically have been considered; the number of receiving channels is two; the type of interference components of the input signal has not been taken into consideration; we have not taken into consideration the impact of a direct signal from the external radiation source on the main receiving channel of a survey RS; the operation of the main and additional receiving channels in survey RS has been synchronized.

Further research should aim to develop the methods for suppressing the penetrating signal in an additional receiving channel.

7. Conclusions

1. We have assessed the detection zone of survey RS under a mode of single-position location. The detection zone under this mode significantly depends on the properties of a single-position AO ESS (a change in the AO foreshortening relative to RS).

2. We have assessed the detection zone of survey RS under a mode of the distributed location. It was established that the dimensions of an AO detection zone under a mode of the distributed location depend not only on the characteristics of the transmitting and receiving positions but on the geometry of the system and the technique of combining information. It was found that changing a bistatic angle could significantly affect the size of the detection zone of stealth AO by RS with the distributed mode of location. It is also established that the size and nature of AO detection zones under a mode of the distributed reception depends on the distance to the base line (the closer AO to the base line, the greater the impact of the ESS dependence value on a bistatic angle) and the degree of suppression of the penetrating signal in the receiving position.

3. We have assessed the detection zone of survey RS when merging the single-position and distributed location

modes. It was established that the shape of an AO detection zone depends on the design features of a particular AO and would take a different form for different types of AO. However, the general tendency to increase the size of the detection zone and reduce the dependence of its shape on the AO foreshortening when merging the single-position and distributed receiving regimes would be inherent in all types of AO.

4. We have assessed the quality of applying the merging of the single-position and distributed receiving modes at the predefined flight altitude of an air object. It was established that the use of the non-coherent merging of the single-position and distributed processing channels can provide for an increase in the size of the detection zone of stealth AO by at least 30 % compared to the size of a single-position RS detection zone.

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