Problematic issues of creating modern ground-based electronic reconnaissance equipment related to radio wave propagation

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Annotation

Considered are the issues of building radio intelligence stations associated with signal distortions on ground paths of radio wave propagation. Two sides of the problem are touched upon. The first of them is the optimization of the construction of reconnaissance stations based on the use of direction finding or differential - range - finding method for determining the coordinates of the radio emission source, taking into account the spatial - temporal distortions of radio signals. The second is the use of a radio wave propagation path for the construction of single-position passive positioning systems.

Introduction

An important component of electronic warfare (EW) is electronic intelligence[1,2]. Radio-technical reconnaissance is carried out from space, from the air and from the ground. The data obtained complement each other. In this paper, ground reconnaissance assets are considered. One of the tasks of ground-based facilities is to determine the location of operating enemy radar stations with an accuracy sufficient to defeat them. At present, the location problem is solved by using direction finding or differential ranging methods for determining coordinates, or their combination. In any case, the reception of signals from the radiation source (RS) is carried out by two or three points, between which a broadband connection must be established to solve the positioning problem. The presence of a communication line unmasks the reconnaissance station, depriving it of its main advantage over active means. A decrease in the distance between reception points is possible on the basis of an increase in the accuracy of goniometric and differential-ranging measurements. The fundamental limitation in increasing the accuracy is the spatial-temporal distortion of radio waves along the propagation path. On land routes, distortions arise under the influence of various kinds of obstacles in the form of relief elements, vegetation, and artificial structures. The purpose of this article is to identify problematic issues in the field of radio wave propagation, the practical solution of which could significantly improve the characteristics of electronic intelligence equipment. You can break these questions down into parts:

• optimization of the construction of reconnaissance means, minimizing the effect of distortion of radio waves;

• using terrain for the construction of modern reconnaissance assets.

Optimization of reconnaissance means for signal distortions along the propagation path

A large number of works are devoted to the study of the amplitude-phase distortions of radio waves on terrestrial propagation paths and the search for methods to minimize their influence on the accuracy of passive means of positioning. We do not review these works here, referring the reader to the monograph [3]. The monograph summarizes the known results in the field of the influence of the radio wave propagation path on the accuracy of passive positioning systems. But its main content lies in the description and analysis of experimental studies in the field of radio wave propagation carried out by the Research Institute of radio engineering systems TUSUR on a new technological basis. The measurements were carried out on medium-intersected ground-ground paths at a distance of up to 30 km in the period from 1995 to 2011.

The measuring complex included a mobile transmitting point of the three-centimeter range and three stationary receiving and measuring points.

The antenna system of the receiving station consisted of eight rectangular horns of orthogonal polarizations, forming two two-base phase direction finders located one above the other. The complex provided digital registration at the receiving point of the quadrature components of the signals, from which their amplitudes and phase differences were reconstructed at the outputs of spaced-apart antennas. The conversion of signals into digital form is carried out with a time step of 11 ns.

Based on the data obtained, the bearing to the radiation source was calculated and the time of signal reception was recorded in the local time scale at the moment they crossed the threshold level.

In fig. 1 schematically shows the elements of the measuring radiophysical complex and the path of propagation of radio waves, T_x – transmitter, , R_x – receiver. An enlarged diagram of one of the eight receiving channels is shown in Fig. 2.

The main feature of the measurements is that the delay of the signal emitted by a pulsed radar with a scanning antenna up to three receiving points was measured at the same time. At each of the points, a synchronous digital recording of the amplitudes and phase differences of signals on spatially separated antennas was carried out with a time interval of 11 ns.

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First, the introduction of corrections to the result of difference - time measurements based on the study of the propagation paths of radio waves over the terrain map in combination with the statistical processing of the signals from the scanning RS at the separated reception points can significantly reduce the error in the positioning of the RS (by tens of times under experimental conditions).

Secondly, the use of full polarization reception of signals and their statistical processing in phase direction finders makes it possible to halve and more reduce the direction finding error of the scanning source [3,5].

Thirdly, if the reconnaissance station simultaneously implements direction finding and differential - rangefinder methods of positioning the RS, and its antenna system is an array of weakly directional elements, then this array can be used for direction finding of the RS by digitally forming a diagram on it directed to the RS with the main lobe antenna radiation patterns. Difference - range measurements are also performed in this statement. On the one hand, this increases the signal-to-noise ratio, on the other, it serves as a spatial filter that reduces the level of radio wave reflections from the terrain. The effectiveness of an adaptive lattice depends on its size and the number of elements.

Fourth, analysis of the amplitude-phase structure of each pulse received by the direction finding system. Complete or partial exclusion from processing of pulses with an excessively large change in bearing [3,6].

Corrupted impulses leading to abnormally large bearing errors in the process of disambiguating measurements in multibase phase direction finders. Under the conditions of the conducted field experiments, the RMS of the bearing in a two-base direction finder decreased by up to 4 times with an insignificant (up to 5%) number of missed pulses [3,7].

Using terrain to build a single-position passive rangefinder

Physical prerequisites for constructing a one-position coordinate determination system

The above ways to reduce the influence of the radio wave propagation path on the accuracy of coordinate measurements allow reducing the rangefinder base of the reconnaissance station, but do not exclude the need to have a communication line unmasking it. Ideal in this respect is the construction of the station when reconnaissance is carried out from one receiving point.

It seems possible to do this by analyzing at the receiving point, along with the direct signal from the source, the signal reflections from objects on the ground. This idea is not new, but in all proposals for its implementation known to us, a priori knowledge of the coordinates of the reflecting point is required. For example, as in the patent [8].

Experimental studies, briefly described in the previous subsection, have shown that on real ground paths at the point of reception, along with the direct signal of RS, there are multiple reflected signals, resolved in time. It is possible to measure the delay of each of them relative to the direct and the bearing to the re-emitter using a mono-impulse method.

An example of a registered implementation is shown in Fig. 3. It shows a typical case when several reflected ones are registered behind the direct signal.

To check that each re-reflected pulse really corresponds to a reflecting object on the ground, the coordinates of the reflection sources were calculated from the delays and bearings of the re-reflections relative to the direct signal. In the calculations, the coordinates of the receiving and transmitting points were considered known.

The obtained coordinates of the reflectors were superimposed on the satellite image of the experiment area. In fig. 4 a) shows a part of the image of the terrain in the area of the transmitter location with forests (dark extended objects), on which the coordinates of the reflectors are superimposed (light circles). The same image without overlapping the coordinates of the reflectors is shown in fig. 4 b).

A random check showed that the calculated coordinates of the reflecting objects coincide with the actual ones with an error less than 10-20 m.

Thus, the re-reflected signals contain information about the coordinates of the radiation source.

Algorithm of a single-position rangefinder

The authors proposed a method for determining the range to the RS of a single-position radio-locator, using a set of reflections, when it is impossible to determine exactly which objects on the map are valid reflectors [9]. Each reflected signal of the RS has its own bearing φ and delay value τ relative to the direct signal. With the known coordinates of the reflecting object, the delay, the range to the RS can be calculated as: $R = 2d\Delta r - \Delta r^2 / 2\left(\Delta r - d(1-\cos\varphi)\right)$, $\Delta r = c\tau$, c - radio propagation speed. Having determined the range, the coordinates of the RS can be found as: $x_{RS} = R\cos\theta$, $y_{RS} = R\sin\theta$. The bearing to the RS θ is measured at the receiving point, and to determine the coordinates of the RS, only the range R needs to be found. Therefore, only the algorithm for determining the range was considered, since only it is an unknown quantity.

If there are a large number of objects on the map, any reflected signal can be associated with many objects that could reflect the signal - potential reflectors.

Potential reflectors are located in the angular sector (as shown in Fig. 5), the center of which is located on the measured bearing line φ, and its angular aperture, with a probability close to 1, is equal to $\Delta_\varphi = 6\sigma_\varphi$, where σ_φ is the RTS of the bearing estimate by the reciever.

One reflected signal corresponds to many estimates of the range to the RS R, among which there is its true value. In the presence of several reflected signals, there is a set of sets, each of which contains a true value R.

On the basis of numerical modeling, it is shown that if an extended object is represented as a contour filled with point objects located at the nodes of the coordinate grid, among which there are real reflectors, the distance to the RS can be found by the maximum of its empirical probability distribution density obtained from the set of potential reflectors.

Consider the methodology for assessing the range to the RS. Let us denote the coordinates of the receiving point as x_R, y_R.

The coordinates of local objects in the considered area of the terrain, entered into the database, will be denoted as a set of row vectors $\mathbf{x} = \left(x_1, x_2, \ldots x_N\right)$, $\mathbf{y} = \left(y_1, y_2, \ldots y_N\right)$, N - the number of objects on the map.

Now we will find a vector $\boldsymbol{\alpha}$ containing the values of the angles from the receiving point for each local object entered on the map. The vector $\boldsymbol{\alpha}$ contains N elements.

1. At the receiving point, a direct signal from radiation sources and n reflected signals are received. For the i-th reflected signal (where $i = 1\ldots n$

), measurements are made of the bearing to the reflecting object and the difference in the propagation time of the direct and reflected signals τ_i.

2. For each measured value φ_i, the vector $\boldsymbol{\alpha}$ contains the numbers of the elements α_k (formally - columns, since the vector consists of one row), the values of which lie in the sector of angles, set by φ_i the size of the angular aperture Δ_φ, as: $\left(\varphi_i - \Delta_\varphi/2\right) < \alpha_k \le \left(\varphi_i + \Delta_\varphi/2\right)$ (fig. 5). Element numbers k are entered into the vector $\mathbf{k^i} = \left(k_1^i, k_2^i, \ldots, k_m^i\right)$. Here m is the number of objects on the map lying in the measured direction $\varphi_i \pm \Delta_\varphi/2$, which are potential reflectors of the received signal. The value σ_φ is determined by the error in measuring the bearing by the equipment of the receiving point to the reflecting object.
3. The vector of range estimates $\mathbf{R}^i$ is calculated, the elements $\mathbf{R}^i = \left(R_1^i, R_2^i, \ldots, R_m^i\right)$ of which are determined as $R_m^i = \dfrac{2d_m \Delta r_i - \Delta r_i^2}{2\left(\Delta r_i - d_m\left(1-\cos\varphi_i\right)\right)}$, $\Delta r_i = c\tau_i$, $d_m = \sqrt{\left(\mathbf{x}\left\{k_m^i\right\} - x_R\right)^2 + \left(\mathbf{y}\left\{k_m^i\right\} - y_R\right)^2}$. An expression $\mathbf{y}\left\{k_m^i\right\}$ means a selection from a vector of $\mathbf{y}$ an element with a number k_m^i.

Repeating the calculations of point 3 for all reflected signals, we get a set of n vectors $\mathbf{R}^i$. In the absence of an error in measuring the parameters of the signal and coordinates of the reflecting objects, the final estimate of the range to the RS $\widehat{R}$ could be found by the maximum distribution density of all the estimates obtained, which can be represented as the intersection point of all the sets formed by the values of the vectors $\mathbf{R}^i$ as: $\widehat{R} = \mathbf{R}^1 \cap \mathbf{R}^2 \cap \ldots \cap \mathbf{R}^i$, where $\cap$ is the intersection operation. This is equivalent to finding the distribution of the range estimates contained in all vectors $\mathbf{R}^i$, the maximum of which will be the true value of the range to the RS.

Due to the influence of various kinds of errors on the measurement results, all vectors will not intersect at the point of true range. Therefore, the range estimate becomes a random variable. When the desired distribution and its maximum are found, a histogram of range estimates is constructed, which, in turn, is an estimate of the distribution density of the range to the RS. An estimate of the distribution density of range estimates is found using the histogram. We will find an estimate of the range as the maximum of the function $S(\Delta R)$: $\widehat{R} = \max\left[S(\Delta R)\right]$.

Results of modeling the operation of a single-position rangefinder

When checking the efficiency of the proposed technique, modeling was carried out for several cases - when there are from one to three extended objects on the path of radio wave propagation. One of them is shown in Fig. 6, when three extended objects are present on the PPB path, spaced apart from each other. The same figure shows a histogram of the distribution density of range estimates, the vertical line marks the true value of the range and the magnitude of the error in determining it from the maximum of the histogram. The distance between the RS and the receiver was R= 5 km. The diameter of objects No. 1-3 is 3 km, 500 m and 2 km, respectively.

The results of the test showed that, within the framework of the adopted model, the proposed methodology makes it possible to determine the distance to the IRR when one or several extended objects are present on the path. However, these results are partial, since they were obtained with a fixed distribution of point reflectors in extended objects and only illustrate the possibility of obtaining an estimate of the range $\hat{R}$. The error in determining the range R_{err} depends on the distribution of point reflectors and their number relative to the total number of potential reflectors included in the extended object. To assess the accuracy of the proposed method, the statistical characteristics of errors in determining the range were calculated for a variety of options for the location of real point reflectors within an extended object, as well as for a different number of them. The number of real reflectors was set as a percentage of the total number of point objects forming one extended object: $\mu = (n/N) \times 100\%$, where n is the number of really reflecting objects, N is the number of all point objects.

In statistical modeling, the influence of the following factors on the error in determining the range R_{err} to the RS was considered:

1) the division value of the coordinate grid Δ, at the nodes of which the reflectors can be located;

2) the relative number of reflectors μ;

3) RMS of the error in determining the bearing to the actual reflector σ_{φ} and RMS of the error in determining the difference in propagation time of the direct and reflected signals σ_{τ}.

The simulation results showed that a decrease in the step of the filling grid of an extended object Δ reduces the error in determining the range R_{err}. For example, a 4-fold decrease in the grid spacing leads to a decrease in the relative error R_{err}^{Σ}/R by an average of 3.4 times, where $R_{err}^{\Sigma}=\sqrt{\bar{R}_{err}^{2}+\sigma_{R_{err}}^{2}}$, $\bar{R}_{err}$ – expectation of ranging error R_{err}. The relative error (at RMS of the bearing and ns delay measurement errors) varies from 8% (= 20 m) to 2.3% (= 5 m). In the cases considered, R_{err} it weakly depends on the number of extended objects participating in the assessment, but depends only on the grid spacing Δ and the relative number of real reflectors μ.

Testing the one-position method on experimental data

To test the proposed technique in real conditions, it is necessary to have data on all objects located on the investigated paths of radio wave propagation, which can reflect the signals of RS. When describing reflecting objects along the paths of radio wave propagation, the following approach was used - it was assumed that only the boundaries of extended objects are potential reflectors.

To compile a map of reflectors, satellite images of the experiment area were used, obtained using the Internet service "GoogleMaps". As a result, the coordinates of all objects were obtained, which can reflect the signals of the RS. The most common type of objects are extended forest tracts.

Unfortunately, with the chosen method of processing two-dimensional maps, some objects are also distinguished that cannot reflect signals in the horizontal plane, for example, roads.

In fig. 7 shows a part of a satellite image of one of the investigated paths of radio wave propagation, after selecting objects on it that can reflect the signals of a radio emission source, and their boundaries.

Based on the processed images, maps of the location of reflective objects were generated. A part of such a map with the designated positions of the transmitter and the axes of the propagation paths of radio waves is shown in fig. 8.

For each investigated path of radio wave propagation (a total of five paths were investigated), the processing of records of received signals extracted from the digital database was carried out. Using the threshold method, direct and reflected signals were isolated. Then, the differences between the moments of detection and the bearing values were calculated. The standard deviation of the bearing measurement error by the equipment of the experimental complex is 0.1 deg, and the moment of signal detection is 60 ns.

The empirical densities of the probability distribution of the range estimates for the case when the potential reflectors are the boundaries of extended objects are shown in fig. 9. The vertical line in the figures marks the actual range to the RS.

From the dependencies shown in Fig. 9, the following conclusions can be drawn:

1) the use of the boundaries of extended objects in the proposed methodology makes it possible to determine the distance to the IRI;
2) when using the boundaries of forest areas, the main maximum of the distribution of range estimates exceeds the rest by 10% - 40%;
3) the main maxima became narrower than when using the entire area of objects, which had a positive effect on the accuracy of determining the range;
4) the technique turned out to be inoperable on track No. 6 - the main maxima of the function are outside the true value of the range.

The results of processing experimental data on determining the range to the IRR on the studied paths are summarized in Table 1. From these data, it follows that the relative error in determining the range to the RS lies in the range from 1.6 to 3.6% (if we assume that the reflectors are distributed throughout area of the object) and 1.2-1.8% if you use the contours of extended objects. On route 6, it was not possible to obtain a correct range estimate.

Table 1 - The results of assessing the range to a radio emission source on real paths of radio wave propagation

Name	R, м	Using the entire area of extended objects		Using only the edges of extended objects	
		R_{err}, м	R_{err}/R, %	R_{err}, м	R_{err}/R, %
Track 1	16689	601	3,6	221	1,3
Track 2	16838	311	1,8	231	1,4
Track 3	16857	353	2,1	313	1,8
Track 4	16985	285	1,6	205	1,2
Track 6	13342	–	–	–	–

From the analysis of the dependencies shown in Fig. 9, the following conclusions can be drawn:

1) the proposed method for determining the range to the RS turned out to be efficient on real tracks;
2) the distribution of estimates of the range to the RS $S(\Delta R)$ is a function with several maxima;

3) on the Track No. 6, the technique turned out to be ineffective - the main maxima of the function are far from the true value of the range.

Studies have shown that the presence of several distribution maxima $S(\Delta R)$ on path No. 6 is a consequence of the fact that most of the reflected signals recorded at the receiving point are reflected from objects located behind the transmitter and have a poor geometric factor.

The carried out numerical simulation confirmed that the exclusion of these reflectors from processing can significantly increase the accuracy of the range measurement.

In general, the results of processing the data of the radiophysical experiment showed that the developed method for determining the coordinates of the RS, using a set of reflected signals, is efficient in real terrain conditions. To exclude large measurement errors, objects that cannot reflect radio waves in the horizontal plane should be removed from the map used, and reflective objects with a poor geometric factor should be removed from the range calculations.

The technical implementation of the method, as shown by experiments, is quite realistic on the basis of monopulse direction finding methods and high-speed digital technology. Moreover, to give the survey monopulse direction finder the properties of a single-position range finder, only the signal processing system should be upgraded. Assigning rangefinder functions to reconnaissance station posts that implement the direction finding method of positioning creates new tactical opportunities for it.

Electronic maps of the terrain necessary for the implementation of the one-position method for determining the coordinates can be created (corrected) according to aerospace photography data before the start of working.

Application of algorithms for homomorphic processing of received signals to determine the value of the delays of reflected signals

The achieved accuracy of positioning the coordinates of the source was achieved when using the threshold method for detecting impulses, both direct and reflected. The increasing complexity of the processing algorithms makes it possible to separate the delayed pulses from the general implementation of the observation window. We represent the signal under study in the form of direct and following a series of reflections

$$y(t) = x(t) + \alpha x(t - \tau) + n(t) \qquad (1)$$

where x (t) is a fixed signal having a spectral power density F (ω), α is the attenuation coefficient, n (t) is the implementation of noise.

Possible approaches for post-processing of data are correlation-extremal algorithms and algorithms for cepstrum (homomorphic processing). The use of the cepstrum approach is to build the cepstrum function

$$C_s(q) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \ln|S(\omega)|^2 \, e^{i\omega t} \, d\omega \qquad (2)$$

where S (ω) is the spectrum of the input signal, q is the cepstrum time.

It was proved [10] that the logarithm of the power spectrum of the vibration containing the reflected signal has an additive periodic component created by this signal, and therefore the Fourier transform of the logarithm of the power spectrum has a peak at the place corresponding to the delay of the reflected signal. The accuracy of determining the moment of delay of the reflected signal directly affects the accuracy of positioning the coordinates of the RS.

The signal is a recording of quadratures within one observation window, digitized by an eight-bit ADC. In the spectral area, the signal can be represented as

$$F_y(\omega) = F_x(\omega)\left(1 + \alpha e^{-i\omega t}\right) + N(\omega) \qquad (3)$$

Having received the cepstrum function of the signal under consideration, the task is to determine the value of the delay of the reflected signals. Figure 10 shows the result of the separation of reflected pulses by the threshold method. The threshold algorithm has identified one reflected pulse with a duration longer than the emitted one. It is not possible to determine the delay from such an impulse.

In fig. 11 on the left, the original signal and its cepstrum function are presented. In the lower right part, the local maxima of the cepstrum function are highlighted, and above the samples of the original signal corresponding to certain delays.

It can be noted that the use of the cepstrum function made it possible to isolate individual reflections from an extended distorted pulse, which provides additional information that can be used to determine the coordinates of the RS. The main disadvantage of using homomorphic processing is high computational costs; however, when using modern computer technology, this is not a particular difficulty in the implementation of algorithms.

Conclusion

Based on the foregoing, the following conclusions can be drawn.

Up to date, experimental data have been accumulated on the features of the propagation of radio waves in the radar range, the use of which can significantly increase the accuracy of the positioning of radioactive sources within the framework of traditional methods.

At the same time, the accumulated experimental material makes it possible to switch from taking into account the spatial and temporal distortions of radio waves along the propagation path to using the terrain for constructing single-position passive positioning systems. This opportunity has emerged recently thanks to advances in high-speed digital signal processing and geoinformation technologies. The given example is an illustration of this possibility and can serve as a basis for the development of a new type of weapon.

More sophisticated signal processing algorithms are required. The use of cepstrum makes it possible to determine the delay of the reflected signal relative to the direct one when the shape of the received signal is distorted relative to the emitted one.

Sources

1. Радзиевский В. Г., Сирота А. А. Теоретические основы радиоэлектронной разведки. 2-е изд, испр. и доп. М: «Радиотехника», 2004. 432 с.

2. Куприянов А.И., Шустов Л.Н. Радиоэлектронная борьба. Основы теории. М: Вузовская книга, 2011. 800 с.

3. Денисов В.П., Шарыгин Г.С., Крутиков М.В. и др. Пространственно-временные искажения сантиметровых радиосигналов на наземных трассах распространения и их влияние на точность пассивных систем местоопределения. Монография. Томск: Томский государственный университет систем управления. и радиоэлектроники, 2014. 502с.

4. Лебедев В.Ю. Анализ методов статистической обработки сигналов в пассивных системах при наличии отражений // Юбилейная X международная научн. – техн. конф. «Радиолокация, навигация, связь»: сб. тр. Воронеж, 2004. С. 1300-1307.

5. Крутиков М.В., Денисов В.П., Скородумов М.П. Оптимизация совместной обработки ортогонально поляризованных сигналов в пеленгаторах

источников излучения с направленной сканирующей антенной //XV международная научн. – техн. конф. «Радиолокация, навигация, связь»: сб. тр. Воронеж,, 2009. Т.3. С. 1674-1680.

6. Аникин А.С., Денисов В.П., Колядин Н.А. Анализ совместного применения методов устранения аномальных ошибок в фазовых пеленгаторах, работающих по сканирующему источнику на наземных трассах // Доклады ТУСУР.2013. № 3(29). С. 5-14.

7. Денисов В.П., Дубинин Д.В., Крутиков М,В., Мещеряков А.А. Алгоритм отбраковки аномально больших ошибок пеленгования фазовым пеленгатором // Доклады ТУСУР. 2012. № 2(26). Ч. 1. С. 36–42.

8. Пат. США №4882590, кл. G01S 3/02, U.S.Cl. 342/453. Method for locating a radio frequency emitter. / E.H. Roland; Заявлено 18.05.1988. Опубл. 21.11.1989.

9. Патент № 2457505 Устройство для определения координат работающей радиолокационной станции / А.А. Гельцер, В.П. Денисов, А.А.Мещеряков; Заявлено 30.09.2010; Опубл. 27.07.2012, Бюл. № 21.

10. О.В.Сытник, С.А. Масалов, Г.П. Почанин. Алгоритм гомоморфной обработки сигналов георадара// Статистическая радиофизика.2015. Т.6(20).№4.С.39-44.

Appendix

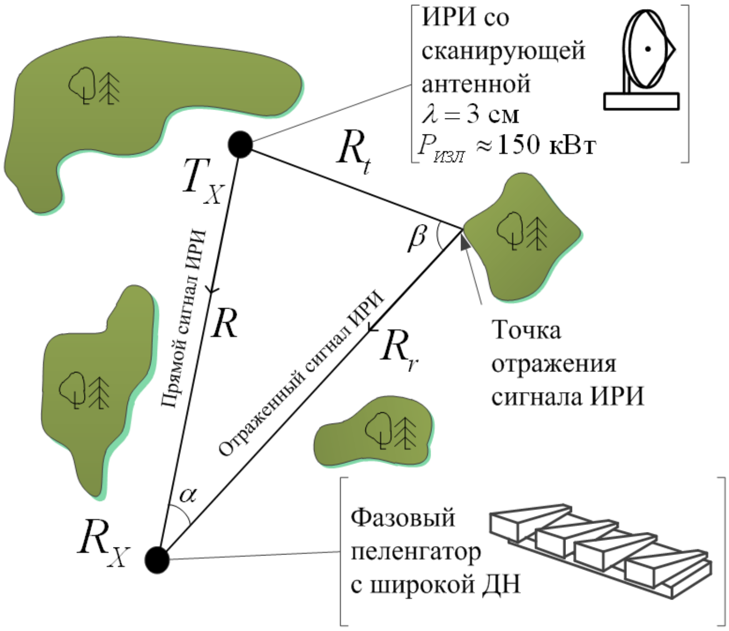

Fig. 1 – Experimental research scheme

Fig. 2 – Block diagram of the receiving channel

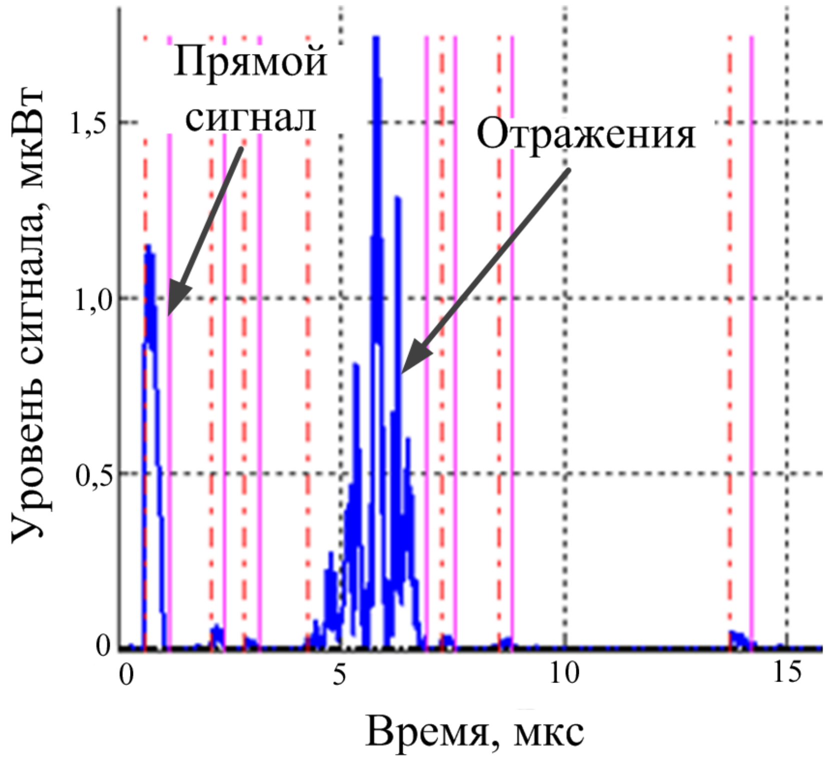

Fig. 3 – An example of the registered implementation of direct and reflected signals

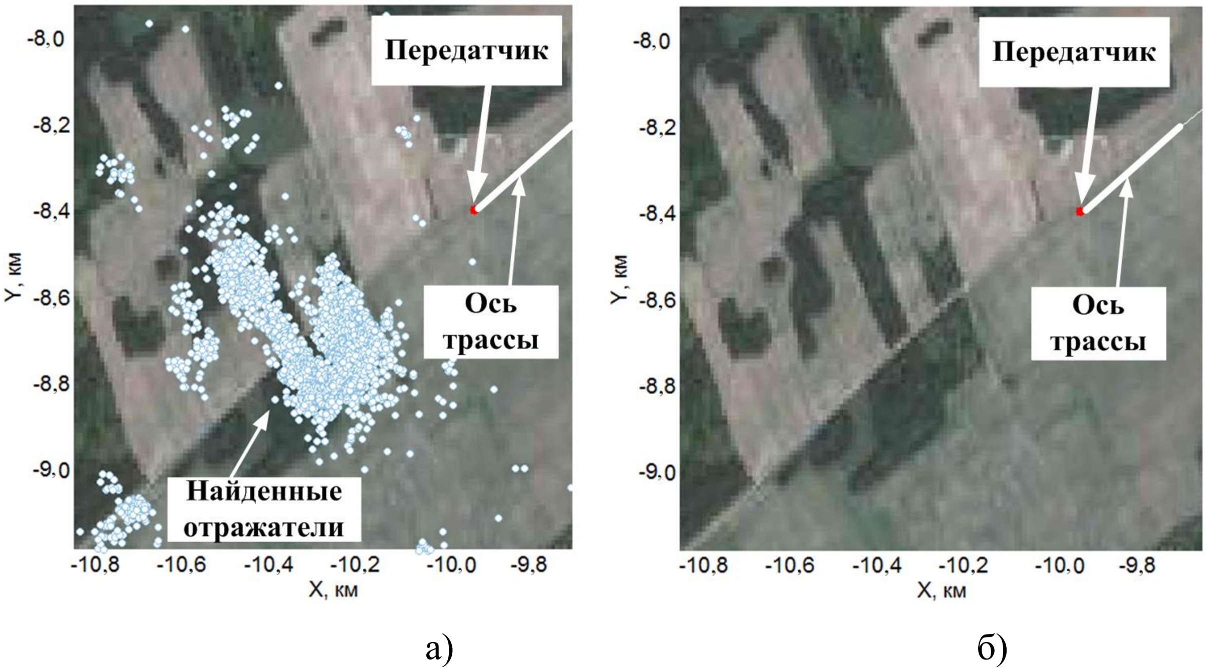

Fig. 4 – A snapshot of the area of the transmitter location with the found coordinates of the reflecting objects

a) with overlapping coordinates of objects, b) without overlapping

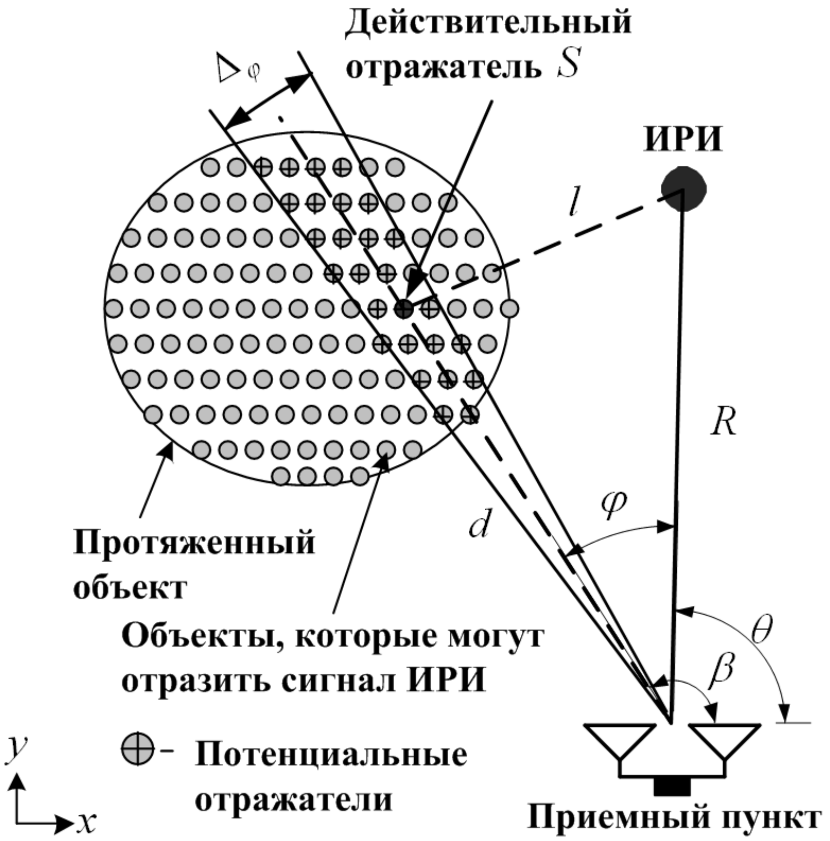

Fig. 5 – Geometric relationships used in the development of a one-position method

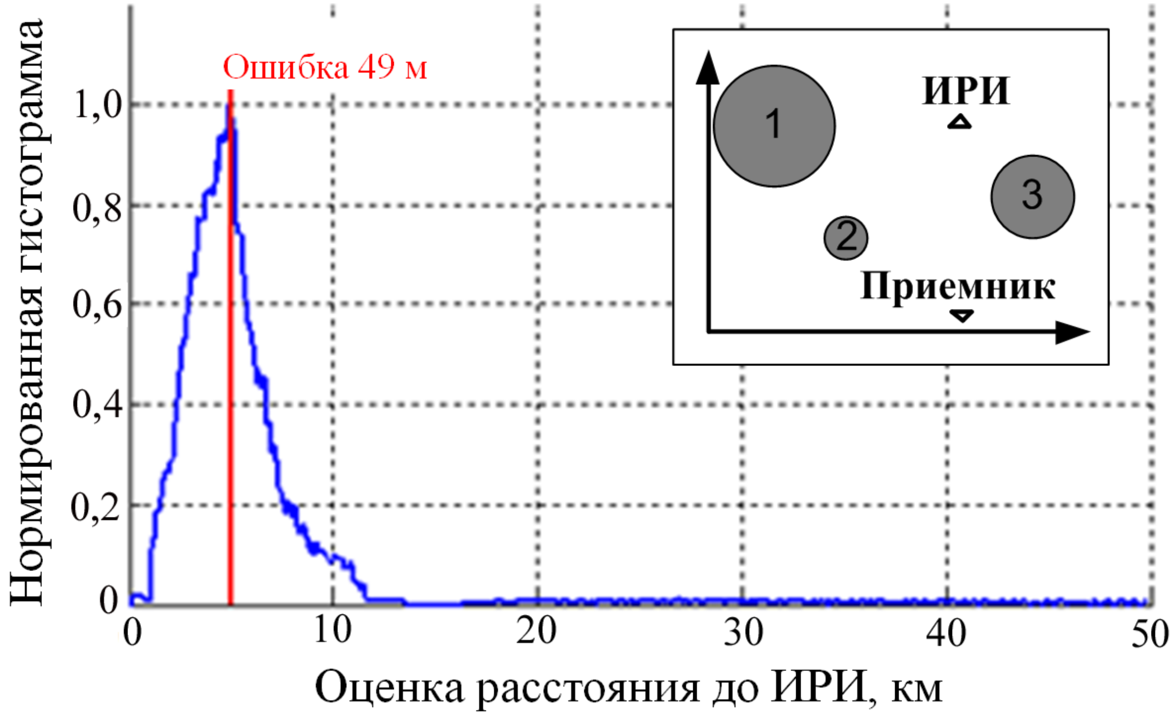

Fig. 6 – Normalized distribution density of range estimates(modeling)

Fig. 7 – Fragments of processed satellite images of the area of the experiment

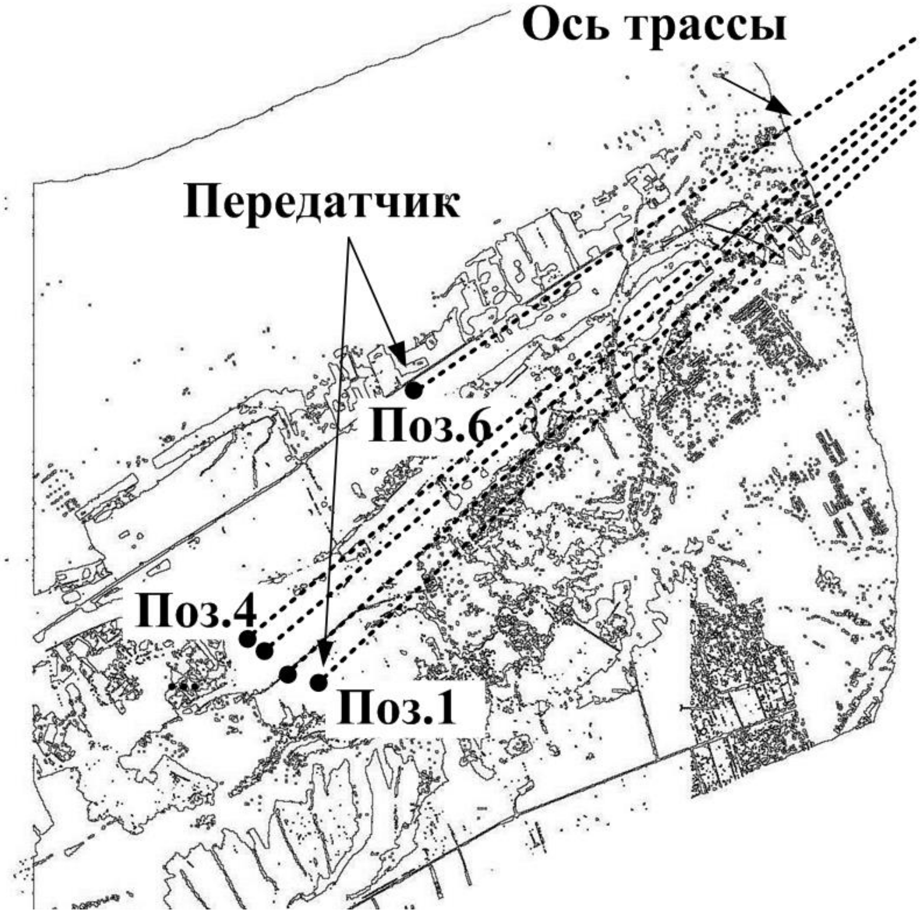

Fig. 8 – Part of the generated map of reflective objects

а) $S(\Delta R)$, трасса №1

б) $S(\Delta R)$, трасса №2

в) $S(\Delta R)$, трасса №3

г) $S(\Delta R)$, трасса №4

д) $S(\Delta R)$, трасса №6

Fig. 9 – Normalized empirical probability distribution densities for range estimates(experiment)

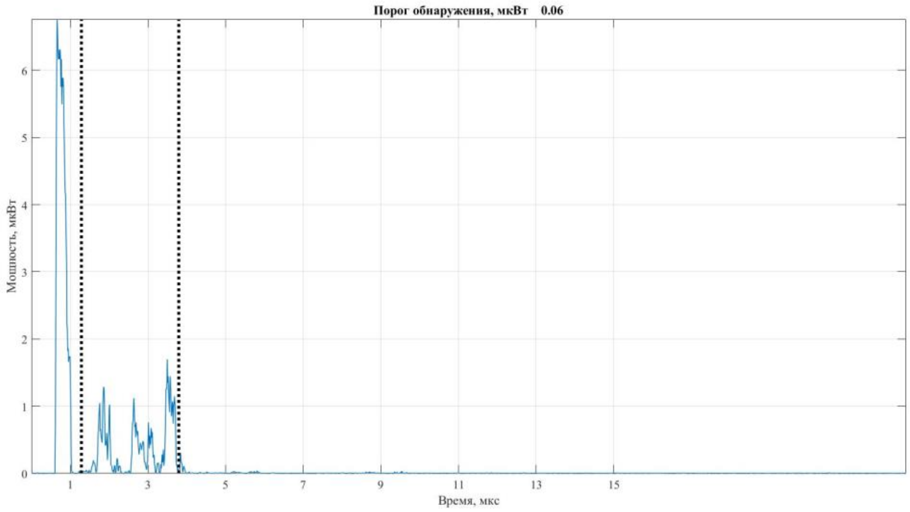

Fig. 10 – Highlighting the reflected impulse (Threshold method)

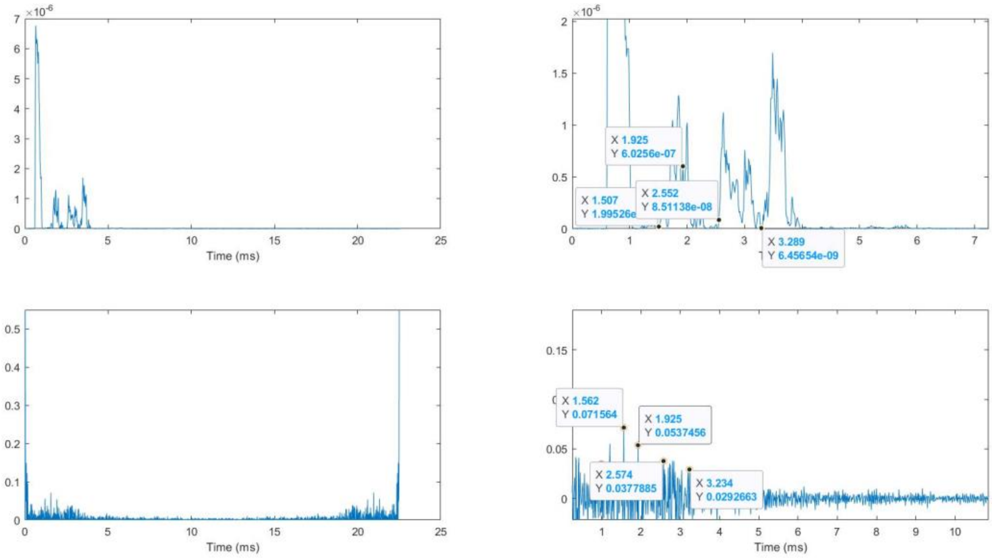

Рис. 11 – Highlighting the reflected impulse (Cepstrum algorithm)