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Maximum detection range of an underwater noise source using holographic processing

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Abstract: **The formation of a hologram of a noise signal from an underwater source against the background of distributed interference is described. An expression is obtained for the bandwidth of the angular distribution of the spectral density of the noise signal on the hologram. The minimum duration of the noise signal is estimated, which determines the maximum detection range of the noise sound source. An algorithm is presented for determining the parameters of holographic processing that realizes the maximum detection range. Holographic processing of noise signals is considered using a single vector-scalar receiver and linear antennas.**

Keywords: **holographic processing, underwater noise source, receiving system, signal duration, detection range**

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Contents

1. INTRODUCTION

Scenarios for the behavior of broadband acoustic signals in oceanic waveguides are extremely diverse and complex, but they obey one general pattern, first established in [1]. It manifests itself in the fact that the interference of the modes of such signals, due to waveguide dispersion, forms a stable interference pattern (interferogram) of the maxima of the energy parameters spectral density of the wave field in the variables of frequency-distance (time). The localized bands configuration is determined by the frequency range, waveguide parameters, speed and source trajectory This pattern is applicable – which is one of its main advantages – also to noise source signals, the description of which is statistical in nature. This allows us to consider the interferogram as a universal deterministic mathematical model of the noise signal and propagation medium. The model is quite simple and at the same time contains a wide variety of forms of behavior. In addition, it has predictive power, but does not require strict causal constraints. In essence, the role of models in physical constructions is determined by how well they convey the real processes essential features.

Based on the interferogram model, a holographic method for detecting and localizing a noise source is proposed and implemented, based on recording a two-dimensional time-frequency interferogram using a two-dimensional Fourier transform [2,3]. The state of the issue of noise signals holographic processing in hydroacoustics is reflected in [4].

This article describes the formation of a hologram of a noise signal from a single source against the background of distributed noise interference in an oceanic waveguide. The conditions for the formation of an undistorted interferogram are given. The angular distribution of the hologram spectral density is discussed. A heuristic criterion for the noise source detection range is formulated. The minimum duration of recording a noise signal, which determines the maximum detection range of the source, has been estimated. Holographic processing of noise signals using a single vector-scalar receiver and linear antennas is considered.

2. HOLOGRAPHIC PROCESSING

We will consider holographic processing of a noise signal $s(t)$ against the background of interference $n(t)$ using the example of sound pressure $p(t)$ recorded by a single receiver. For the vector components of a vector-scalar receiver, the consideration is similar. During the observation time Δt in the frequency band Δf, J independent time noise realizations $p(t) = s(t) + n(t)$ with duration T and with a time interval δT between them are accumulated

$$J = \Delta t/(T + \delta T). \quad (1))$$

Realizations are independent if $\delta T \geq 1/\Delta f$. The Fourier transform restores the time-frequency representation of noise implementations $p(f,t) = s(f,t) + n(f,t)$ and generates a sound pressure interferogram

$$\begin{aligned} I(f,t) &= p(f,t)\,p^*(f,t) = \\ &= |s(f,t)|^2 + n(f,t)\,s^*(f,t) + \\ &+ s(f,t)\,n^*(f,t) + |n(f,t)|^2, \end{aligned} \quad (2)$$

where the superscript "*" denotes the complex conjugate quantity. The first and fourth terms (2) give the spectral density of the signal and noise in the (f,t) plane, and the second and third terms give the mutual spectral densities of the signal and noise. Since the signal and noise are uncorrelated, the mutual spectral densities will have the form of a low-contrast smeared background and its weight in the interferogram $I(f,t)$ can be neglected. Consequently, interferogram (2) can be approximately represented as a linear combination of signal and noise interferograms

$$\begin{aligned} I(f,t) &\approx |s(f,t)|^2 + |n(f,t)|^2 = \\ &= I_s(f,t) + I_n(f,t). \end{aligned} \quad (3)$$

The sound pressure hologram taking into account relation (3) takes the form

$$\begin{aligned} F(\tau,\nu) &\approx \int_0^{\Delta t}\int_{f_1}^{f_2} \left[I_s(f,t) + I_n(f,t)\right] \exp\left[i2\pi(\nu t - f\tau)\right] df dt = \\ &= F_s(\tau,\nu) + F_n(\tau,\nu). \end{aligned} \quad (4)$$

Here ν and τ are the frequency and time of the hologram; $f_{1,2} = f_0 \mp (\Delta f/2)$ – average frequency of the spectrum. In the hologram, the spectral density of the signal $F_s(\tau,\nu)$ of a moving source is concentrated in two narrow bands, mirror-inverted relative to the origin, in the form of focal spots caused by the interference of modes of different numbers. They are located in the first and third quadrants of the hologram if the radial velocity of the source is $w < 0$ (the source approaches the receiver), and in the second and fourth quadrants ($w > 0$) when the source moves away from the receiver. Radial velocity refers to the projection of the source velocity in the direction of the receiver. When the source is stationary and moves along a circular arc, the coordinates of the peaks of the focal spots are located on the time axis τ. The concentration region contains $(M - 1)$ main maxima with coordinates (τ_μ, ν_μ) located on the straight line $\nu = \varepsilon\tau$ with the angular coefficient $\varepsilon = \nu_\mu/\tau_\mu$ where M is the number of modes forming the field and is the number of the focal spot. The maximum of the first focal spot closest to the origin of coordinates is due to the interference of neighboring modes and falls on the values (τ_1, ν_1). The coordinates of the neighboring peak caused by the interference of mode numbers $(m, m + 2)$ are located at the point (τ_2, ν_2), etc. And finally, the coordinates of the most distant peak, dictated by the interference of the first and last modes – $(\tau(M - 1), \nu(M - 1))$. At points with coordinates (τ_μ, ν_μ), the $(M - \mu)$ main maxima are summed up. The spectral noise density $F_n(\tau, \nu)$ is distributed over the entire plane (τ, ν) of the hologram.

Under the condition $r_0 \gg |w|\Delta t$, where r_0 is the distance of the source from the receiver at the initial time $t = 0$, the radial speed and distance are equal

$$\dot{w} = -2\pi\kappa_{w\mu}\nu_\mu,\ \dot{r}_0 = \kappa_{r\mu}\tau_\mu, \tag{5}$$

$$\kappa_{w\mu} = \left[\overline{h_{m(m+\mu)}(f_0)}\right]^{-1}, \quad \kappa_{r\mu} = 2\pi\left[\overline{dh_{m(m+\mu)}(f_0)/df}\right]^{-1} \tag{6}$$

– coefficients that determine the spatial and frequency scales of variability of the waveguide transfer function [5]. Here $h_{mn} = h_m - h_n$, h_m is the horizontal wave number of the m-th mode. The restored source parameters, in contrast to their true values, are marked with a dot at the top. The bar above means averaging over mode numbers. For the first ($\mu = 1$) and last ($\mu = M - 1$) focal spots limiting the localization region of the signal spectral density, relation (6) is simplified

$$\kappa_{w1} = (M-1)\left[h_{1M}(f_0)\right]^{-1},$$
$$\kappa_{r1} = 2\pi(M-1)\left[dh_{1M}(f_0)/df\right]^{-1}, \tag{7}$$
$$\kappa_{w(M-1)} = \kappa_{w1}/(M-1),\ \kappa_{r(M-1)} = \kappa_{r1}/(M-1).$$

The spectral density of the signal is concentrated in a band limited by straight lines

$$\nu_1 = \varepsilon\tau + \delta\nu,\ \nu_2 = \varepsilon\tau - \delta\nu, \tag{8}$$

where $\delta\nu = 1/\Delta t$ is the half-width of focal spots in the direction of the ν axis. Outside this band, the spectral density of the signal is practically suppressed. Along the τ axis, the half-width of focal spots is $\delta\tau = 1/\Delta f$. The angular coefficients of the direct location of the maxima of focal spots ε and interference fringes $\delta f/\delta t$ are related by the relation

$$\varepsilon = -\delta f/\delta t, \tag{9}$$

where δf is the frequency shift of the wave field maximum over time δt.

3. UNDISTORTED INTERFEROGRAM

The interference pattern formed by a noise source is characterized by frequency and time scales of variability caused by the interference of the mth and nth modes [5]:

$$\Lambda_f^{(mn)} = \frac{2\pi}{r\left|dh_{mn}(f_0)/df\right|},\quad \Lambda_t^{(mn)} = \frac{1}{\left|wh_{mn}(f_0)\right|}. \tag{10}$$

The recorded interferogram and hologram are not distorted if the band Δf and observation time Δt for any pair (m,n) of modes satisfy the conditions

$$\Delta f > \Lambda_f^{(mn)},\qquad \Delta t > \Lambda_t^{(mn)}. \tag{11}$$

Inequalities (11) impose lower restrictions on the reception bandwidth and observation time depending on the distance, radial velocity and time-frequency scales of variability of the waveguide transfer function during the formation of the interferogram. An increase in the bandwidth and a decrease in the average frequency of the spectrum causes a decrease in the distance at which the observed interferogram and hologram are not distorted. Increasing the observation time reduces the permissible values of the radial velocity. Violation of condition (11) leads to a change in configuration and blurring of focal spots, accompanied by an increase in the error in reconstructing source parameters (5). Inequalities (11) are most critical with respect to neighboring modes that form the first focal spot. If the first (left) condition is not met, localization of bands of interfering (*m,n*) modes is not observed. A different pattern appears when the second (right) condition is not met, when the observation time is not enough for the source to cross the spatial scales of the interferogram variability. In this case, the position of the peak of the focal spot of such interfering modes is shifted to the time axis of the hologram, so that in relation to them the interferogram is formed as if by a stationary source. If the interferogram is distorted, the source parameters (5) are restored with respect to the undistorted configuration of the focal spots.

4. ANGULAR DISTRIBUTION OF THE SPECTRAL DENSITY OF THE HOLOGRAM

The angular distribution of the signal spectral density $F_s(\tau,\nu)$ on the hologram (detection function) is described by the expression

$$G_s(\chi)=\int_0^{\Delta\tau}\left|F_s(\tau,\chi\tau)\right|d\tau, \qquad (12)$$

where $\Delta\tau$ is the linear size of the concentration area along the time axis τ; χ – variable value of the angular coefficient when integrating along straight lines $\nu = \chi\tau$. When the source approaches the receiver, $0 \le \chi < \infty$, in the case of distance – $-\infty < \chi \le 0$. The maximum signal detection function is achieved at the value $\chi = \varepsilon$. For illustration in **Fig. 1** shows the experimental results of holographic processing of a pneumatic source signal when approaching a single vector-scalar receiver. Accumulation time Δt = 10 min. Input signal-to-noise ratio (s/n) q_0 = 25.5 (14.1 dB). In Fig. 1*b*, the dotted line and squares respectively show the straight line $\nu = \varepsilon\tau$, on which the peaks of the focal spots are located, and the straight lines $\nu_{1,2}$ (8), limiting the spectral

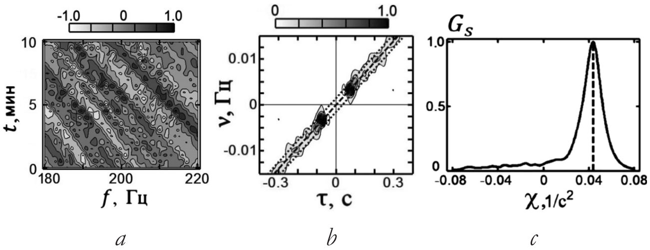

Fig. 1. *Normalized interferogram (a), hologram (b) and detection function (c)*[2].

density. In Fig. 1*c*, the vertical dotted line marks the value $\chi = \varepsilon$.

Bandwidth of the detection function, according to Fig. 1*c*, at the level of 0.1 and 0.5 from the maximum is $\Delta\chi_{0.1}$ = 0.048 s^{-2} and $\Delta\chi_{0.5}$ = 0.018 s^{-2}. The width of the band $\Delta\chi_{0.1}$ can be estimated from the condition as the difference in the angular coefficients of the straight lines $\nu = \chi\tau$ passing through the points (τ_1, $\varepsilon\tau_1 + \delta\nu$), ($\tau_1$, $\varepsilon\tau_1 - \delta\nu$), and the width of the band $\Delta\chi_{0.5}$ – through the points ($\tau_{(M-1)}$, $\varepsilon\tau_{(M-1)} + \delta\nu$), ($\tau_{(M-1)}$, $\varepsilon\tau_{(M-1)} - \delta\nu$). As a result we get

$$\Delta\chi_{0.1} = 2/\Delta t\tau_1,\ \Delta\chi_{0.5} = 2/\Delta t\tau_{(M-1)}. \qquad (13)$$

From Fig. 1*b* it follows that τ_1 = 0.066 s^{-2}, $\tau_{(M-1)}$ = 0.22 s^{-2}. According to (13), the bandwidth is $\Delta\chi_{0.1}$ = 0.050 s^{-2} and $\Delta\chi_{0.5}$ = 0.015 s^{-2}, which is close to the experimental values. The bandwidth $\Delta\chi$ of the detection function, according to (5) and (13), is determined by the accumulation time, distance, frequency scales of variability of the waveguide transfer function and does not depend on the width of the signal spectrum and the radial velocity of the source. It decreases with increasing observation time Δt, distance r_0 and decreasing average frequency of the spectrum f_0. The smaller the bandwidth, the more accurate and reliable the estimate of the slope ε.

5. HEURISTIC CRITERION FOR SOURCE DETECTION RANGE

As a heuristic criterion for the detection range of a noise source, the condition is accepted that the maximum of the detection function of the noise implementation of the signal against the background of interference

$$G(\chi, q_0) = \int_0^{\Delta\tau} \left| F(\tau, \chi\tau, q_0) \right| d\tau \qquad (14)$$

in the direction $\chi = \varepsilon$ the location of the peaks of the focal spots of the signal is two or more times higher than the interference level in the directions $\chi \neq \varepsilon$ at the input ratio s/n q_0

$$q = G(\varepsilon, q_0) / G(\chi, q_0). \qquad (15)$$

The position of the maximum peak is taken as the estimate of ε, $maxG(\chi) = G(\varepsilon)$. In this case, the reconstructed estimates of the source parameters (bearing, distance, radial velocity and depth) are close to real values [2,3]. If condition (15) is not met, then interference peaks appear in the detection function, which increase as the input s/n ratio q_0 decreases and mask the peak of the noise signal. The ambiguity in determining the angular coefficient ε corresponding to the noise signal increases, and the reliability of source detection decreases.

For given processing parameters (accumulation time Δt, frequency range Δf, duration of noise realizations T and the interval between them δT) and the input ratio s/p q_0, the maximum detection range rmax is realized when equality (15) is satisfied. As an example in **Fig. 2, 3** show the results of holographic processing obtained by numerical simulation in the transition region of maximum detection distances of a moving noise source against the background of interference. Processing parameters: Δf = 900-950 Hz, Δt = 30.60 s, T = 1.5 s, δT = 0.5 s, J = 15.30.

With the number of time intervals J = 15.30, according to criterion (15), the maximum detection ranges are estimated as r_{max} = 6 km (Fig. 2) and r_{max} = 9 km (Fig. 3), which correspond to the input ratios s/n q_0 = –8.99, –12.07 dB. Fig. 2*c* and 3*c* show that doubling the number of time samples entails a halving of the bandwidth $\Delta\chi_{0.5}$. With a further decrease in the input s/n ratio, the signal is masked by interference, and ambiguity arises in determining the position ε of the maxima of the detection functions (Fig. 2*i*, 3*i*). Detection of the source at distances r = 7, 10 km becomes impossible. Distances r = 7, 10 km correspond to input s/p ratios q_0 = –10.14, –12.84 dB. At the same time, from Fig. 2*b,e*, 3*b,e* it follows that the configuration of the first focal spots is distorted, since the time coordinate of the position of their peak is located on the time axis, i.e. for neighboring interfering modes, the right-hand condition (11) is violated.

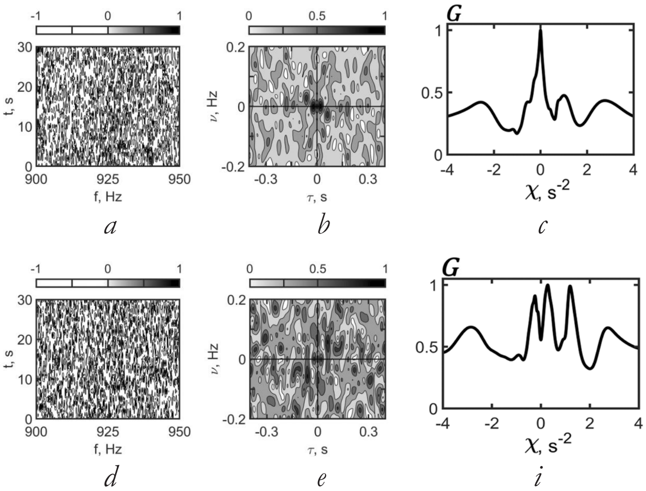

Fig. 2. *Normalized interferograms (a, d), holograms (b, d) and detection functions (b, i). Distances: (a – c) – r = 6 km, (d – i) – r = 7 km. Accumulation time Δt = 30 s, number of noise realizations J = 15* [6].

By the ratio s/p q at the output of holographic processing, taking into account criterion (15), we agree to understand the quantity

$$q = G(\varepsilon, q_0) / G(\chi, q_0). \qquad (16)$$

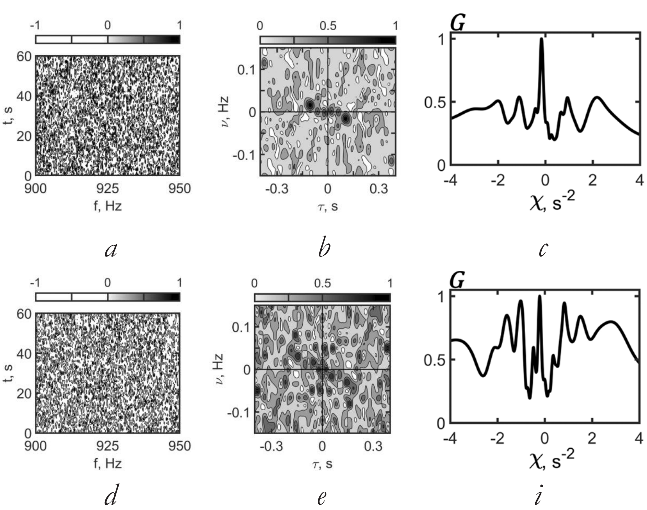

Fig. 3. *Normalized interferograms (a, d), holograms (b, d) and detection functions (c, i). Distances: (a – c) – r = 9 km, (d – i) – r = 10 km. Accumulation time Δt = 60 s, number of noise realizations J = 30* [6].

Then, assuming that the frequency shifts of the interference maxima of the wave field accumulate coherently, and the interference incoherently, expression (16) takes the form

$$q = Jq_0. \tag{17}$$

For a fixed value of temporary noise realizations J, the maximum detection range rmax of a noise source, according to (15), (16), is determined by the implicit expression

$$2 = Jq_0(r_{\max}), \tag{18}$$

where the value $q_0(r_{\max})$ is determined by the law of decay of the average noise emission power of the source with distance and interference level. Thus, for a fixed accumulation time Δt, the maximum detection range rlim is achieved with a minimum duration $T_{\min}$ of the noise signal, i.e. at maximum J value.

6. MAXIMUM DETECTION RANGE

We will estimate the minimum duration of the noise signal from the representation of the signal using frequency samples of the waveguide transfer function. In this case, it is sufficient to limit ourselves to considering the smallest frequency scale of field variability caused by interference between extreme modes.

In accordance with (10), the smallest frequency scale in the vicinity of the frequency f_0 at a distance r between the source and receiver

$$\min\Lambda_f = \frac{2\pi}{r\left|dh_{1M}\left(f_0\right)/df\right|}. \tag{19}$$

The period of signal variability is determined by independent values of the transfer function at five points. The frequency interval δf between two samples should not exceed the value $1/T$, $\delta f \le 1/T$, where T is the duration of the noise signal, therefore value (19) is also equal to

$$\min\Lambda_f = 5\delta f = 5/T. \tag{20}$$

From (19), (20) it follows that the duration of the noise implementation must satisfy the inequality

$$T \ge T_{\min} = \frac{5}{2\pi} r\left|dh_{1M}\left(f_0\right)/df\right|, \tag{21}$$

so that with increasing distance r and decreasing average frequency f_0 of the spectrum, the minimum time for recording a noise signal increases.

As a result, the admissible number of independent time noise realizations (1) is estimated from above as

$$J \le J_{\max} = \frac{\Delta t}{\left(5/2\pi\right) r\left|dh_{1M}\left(f_0\right)/df\right| + \left(1/\Delta f\right)}. \tag{22}$$

By choosing the spectrum width Δf it is almost always possible to ensure that the condition is satisfied

$$J_{\max} \approx \frac{2\pi}{5} \frac{\Delta t}{r\left|dh_{1M}\left(f_0\right)/df\right|}. \tag{23}$$

If the registration duration T is less than $T_{\min}$ (21), this leads to distortions in the reconstruction of the signal spectrum, which entails an increase in the error in determining the position of the focal spot maxima and, as a consequence, an increase in the error in estimating the distance and radial velocity of the source. For the input ratio s/n q_0 ($r_{\lim}$) for the maximum detection range of a noise source, according to (18) and (23), we obtain an implicit estimate.

$$r_{\lim} = \frac{2\pi}{10} \frac{\Delta t}{\left|dh_{1M}\left(f_0\right)/df\right|} q_0\left(r_{\lim}\right), \tag{24}$$

A characteristic feature of relation (24) for the maximum range rlim of a noise source is the fact that it includes parameters of the waveguide transfer function, the physical content of which varies depending on the water area. Recall that expression (24) relates the maximum detection range to the input ratio of a single receiver.

Let us generalize estimate (24) to linear antennas. Let us assume that the interference at the input of the antenna elements is not correlated. To satisfy this condition, it is sufficient to require the inequality $d \ge \lambda/2$, where d and λ are the interelement distance and wavelength. Then expression (24) takes the form

$$r_{\lim(an)} = \frac{2\pi}{10} \frac{\eta}{b} \frac{\Delta t}{\left|dh_{1M}\left(f_0\right)/df\right|} q_{0(an)}\left(r_{\lim}\right), \tag{25}$$

where η and b are the gain and the number of antenna elements, $q_{0(an)}$ is the s/n ratio at the input of a single antenna element [7]. In the case of a horizontal linear antenna, the maximum noise immunity of holographic processing is achieved at a bearing equal to the compensation angle, with $\eta = b^2$. For a vertical antenna $\eta \approx b^2$. If we set $b = 1$, then formula (25) becomes the corresponding formula for a single receiver.

An algorithm for implementing holographic processing parameters at the maximum detection range using the example of a single receiver is presented below.

1. An a priori model of the waveguide is introduced. The maximum detection range rlim is set and the processing parameters are selected: accumulation time Δt, bandwidth Δf and average spectrum frequency f_0. The level of interference is fixed. The dependence of the power of the noise source on the distance r is modeled.

2. Based on the dependence (r) for the maximum detection range r_{lim}, the input ratio s/n is calculated.

3. From expression (24) the value $|(dh_1M(f_0))/df|$ is found, which determines the minimum duration of the noise implementation T_{min}.

4. According to (21), assuming $r = r_{\text{lim}}$, the minimum duration T_{min} of the noise signal is determined.

The described algorithm does not require prior knowledge of the number of energy-carrying modes that form the field at the maximum distance. Therefore, it is applicable to both model and real waveguides. Let us consider the fruitfulness of the algorithm using the example of a numerical experiment [6]. Initial data: $\Delta f = 50$ Hz, $f_0 = 925$ Hz, $\Delta t = 30$ s, = –61.01 dB, $r_{\text{lim}} = 15$ km. Dependence (r) is shown in Fig. 2 [6], from which it follows that $q_0(r_{\text{lim}}) = 2.87\cdot10^{-2}$ (–15.42) dB. According to (24) we have $|(dh_1M(f_0))/df| = 3.61\cdot10^{-5}$ s/m. Using (21), we obtain the estimate $T_{\text{min}} = 4.31\cdot10^{-1}$ s. Note that expression (23) is justified, since the inequality T_{min} » $(1/\Delta f)$ is satisfied.

7. CONCLUSION

The fruitfulness of the holographic method for detecting and localizing underwater noise sources stems from the extreme ease with which the two-dimensional Fourier transform performs the rather complex and intricate linear transformation required to image the source. This simplicity is determined mainly by the fact that the interferogram of a noise signal against the background of interference is represented as a linear combination of interferograms of the signal and interference, on the one hand, and the preservation of amplitude and phase information, on the other.

In this case, a very important role is played by the detection function, which determines the time-frequency focusing of the noise signal, which makes it possible to explicitly determine the maximum detection range of the source depending on the processing parameters and the input signal-to-noise ratio. The expression for the maximum detection range is obtained in relation to a single receiver and linear antennas. The algorithm for determining the maximum detection range was tested in a numerical experiment using a single receiver as an example.

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