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RESEARCH OF THE EFFECTIVENESS OF A RADIO RANGEFINDER WITH CORRELATION PROCESSING UNDER CONDITIONS OF NON-GAUSSIAN PULSE INTERFERENCE

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Abstract—This article studies the operation of a radio rangefinder with correlation processing of a broadband signal under conditions of interference of various types. The article considers the structural model of the radio rangefinder and reveals the key mechanisms of its operation. Separately, the procedures for calculating the signal delay time and integrating the Doppler compensation contour are considered, the use of which is a mandatory condition for preventing degradation (blurring) of the correlation maximum during object movement. The operation of the structural model of the radio rangefinder is modeled in the MATLAB environment under the influence of white Gaussian noise, impulse noise with a Laplace distribution, and non-Gaussian interference with a K-distribution, which are characteristic of reflections from the underlying surface. As a result of the study, the limiting values of the signal-to-noise ratio at which the system is able to correctly distinguish objects were determined: more than -29 dB for white noise, -27.5 dB for K-distribution noise and -21.3 dB for a mixture of white and impulse noise. In addition, the simulation results confirmed the high accuracy of the system: the range measurement error is 0.0625 m, and the resolution reaches 0.375 m. The results obtained prove the feasibility of using the proposed approach for stable navigation of unmanned and manned vehicles in difficult interference conditions.

Keywords—Radar system, radio engineering system, measurement, correlation, signal processing, aeronavigation system, radio-electronic system, noise, K-distribution.

I. INTRODUCTION

The functioning of the navigation systems and autopilot systems, which are equipped with both drones and manned aircraft, is impossible without constant access to highly accurate indicators of the height and distance of objects. The basic tool in such measuring equipment is radio rangefinders [1], [2].

Navigation in dense urban areas, automatic landing, and low-altitude flight around terrain require impeccable accuracy in determining distance. Since the slightest errors during such operations can provoke emergency situations, improving the accuracy of radar operation is a fundamental prerequisite for minimizing hazards and overall increasing flight reliability [2], [3].

A separate challenge is the operation of radio rangefinders in real, interference-laden environments. The target signal undergoes severe degradation not only due to powerful thermal noise or multipath effects, but also due to intense counteraction from electronic warfare equipment and powerful echoes from the surface under the aircraft. As a result, background noise loses its Gaussian properties. Traditional reception

algorithms, oriented to the Gaussian noise model, are powerless in such conditions, which generates critical errors in distance calculations [4].

To achieve high accuracy and stable operation in conditions of intense interference, it is necessary to transition to a correlation reception architecture and use modernized correlation analysis methods. By maximizing the signal-to-noise ratio, correlation processing allows you to confidently capture useful data even with a critically weak signal, while ensuring proper immunity to interference [5], [6].

Therefore, there is an urgent scientific and engineering need to create and optimize efficient methods for processing radar data. These approaches should be based on the theory of optimal correlation reception to ensure maximum distance measurement accuracy and robustness of modern radio rangefinders.

II. REVIEW OF LATEST ARTICLES

In the publications [7] – [9], the feasibility of correlation processing of broadband signals as one of the promising areas in radar is substantiated. This approach allows to improve spatial resolution,

increases measurement accuracy and provides reliable protection against external interference. Such advantages form the basis for the design of innovative radar equipment with improved tactical and technical characteristics.

III. PROBLEM STATEMENT

The operation of radio rangefinders is based on the fundamental principles of electrodynamics. The main point is that electromagnetic waves are able to reflect from obstacles and move in space in a straight line at a constant speed. It is thanks to these physical phenomena that radio radiation serves as a reliable tool for non-contact determination of spatial coordinates of objects. To determine the range to the target, it is necessary to measure the time during which the probing radio signal covers the distance to the object and back [10] – [13].

The mathematical model of a broadband probing signal is given by the following formula:

$$u_c(t) = U_{c_0} \sin(2\pi \cdot f_{c_0} t + \beta_0 p_t), \quad (1)$$

In this expression, U_{c_0} defines the amplitude, and the parameter β_0 is the modulation index; the element p_t denotes a specific random sample from the array p at time t . Thus, we have a signal with a quasi-random phase that varies according to a known law.

The reflected signal receives a time delay τ , and in the case of a moving target, also a change in frequency f_D due to the Doppler effect, which is formalized by the following equation:

$$u_c(t + \tau) = U_c \cdot \sin(2\pi(f_{c_0} + f_D) \cdot (t + \tau) + \beta_0 p_{t+\tau}) + n, \quad (2)$$

Here U_c denotes the amplitude of the received signal; τ is the time delay of the signal; the value f_D is responsible for the Doppler frequency shift, and $p_{t+\tau}$ is a pseudo-random sample from the array p for the moment $t + \tau$, n is noise.

The task is to estimate the delay time τ .

The estimation algorithm consists in maximizing the cross-correlation integral:

$$g(\tau) = \int_{-\infty}^{\infty} u_c(t) \cdot u_c(t + \tau) dt. \quad (3)$$

The vector of parameter estimates is searched according to the rule

$$(\hat{\tau}, \hat{f}_D) = \arg \max_{\tau, f_D} \left| \int_{-\infty}^{\infty} u_c(t) \cdot u_c(t + \tau) e^{-j2\pi f_D t} dt \right| \quad (4)$$

If there is one object and it is stationary ($f_D = 0$), a clearly pronounced peak on the graph of the cross-correlation function (CCF) in the coordinate equal to the delay time τ .

If there are several objects, then more than one peak is formed.

Having information about the speed of propagation of an electromagnetic wave in space c and measuring the signal delay time τ , it is possible to determine the exact distance to the object D . For this calculation, the formula [10], [11] is used:

$$D = \frac{c \cdot \tau}{2}. \quad (5)$$

The Doppler effect is used for radar measurement of the radial velocity of an object V_r . The relationship between the Doppler frequency f_D and the radial velocity of the target V_r is mathematically expressed by the following equation [10], [11]:

$$V_r = \frac{f_D \cdot c}{2 f_{c_0}}, \quad (6)$$

where f_{c_0} is the carrier frequency of the radiated signal.

The aim of the article is to study the efficiency of the correlation rangefinder with a broadband noise-like probing signal under conditions of interference of various types. To solve this problem, methods of computer modeling of the rangefinder operation under conditions of influence of white noise, impulse noise and noise with K-distribution are used.

IV. THE METHOD

The technical implementation of the algorithm (4) is presented by the structural diagram of the radio rangefinder in Fig. 1. The given graphic image comprehensively reveals the path of the signal, starting from the stage of its generation and up to the final calculation of the distance.

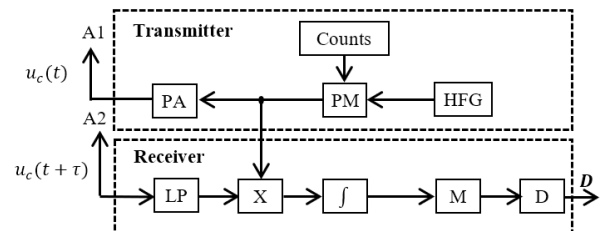


Fig. 1. Structural diagram of a correlation radio rangefinder: transmitting antenna – A1, receiving antenna – A2, power amplifier – PA, phase modulator – PM, high-frequency generator – HFG, linear path – LP, multiplier – X, integrator – J, peak meter – M, distance determination module – D

Fig. 5. Block diagram of a correlation radio rangefinder with Doppler shift compensation

The operation of the structural diagram in Fig. 5 was modeled in the MATLAB environment. The graphs in Fig. 2 and Fig. 4 were generated from the data of this simulation.

V. IMPACT OF NOISE ON SYSTEM OPERATION

The accuracy of radio rangefinders depends largely on the quality of the received signal. One of the main factors that negatively affects the operation of radio rangefinders is noise.

This section presents the results of the simulation of the system operation in the MATLAB environment in the presence of white noise, K-distribution noise, and a mixture of white and impulse noise. The simulation was performed for the following characteristics of the probing signal: the amplitude of the probing signal $U_c = 1V$, несущая частота $f_c = 4\text{ GHz}$, the modulation index $\beta_0 = 1$, the number of signal samples $n = 8000000$.

White noise is a random process that has a uniform energy distribution over all frequencies in a given range. Its amplitudes are distributed according to the normal (Gaussian) law [10]. Sources of such noise are thermal (Johnson) noise, cosmic background, quantum fluctuations of vacuum, random processes in electronic circuits, etc.

Figures 6 – 11 shows the cross-correlation functions in the presence of white noise with a Gaussian distribution for different values of the standard deviation σ and signal-to-noise ratios (SNR). Graphs 6–8 show the results of the simulation in the presence of two objects: the first object at a given distance $D_1 = 110\text{ m}$ ($\tau \approx 0.733\text{ }\mu\text{s}$) with a given radial velocity $V_{r1} = 110\text{ m/s}$ ($f_{D1} \approx 2.933\text{ kHz}$); the second object at a given distance $D_2 = 310\text{ m}$ ($\tau \approx 2.07\text{ }\mu\text{s}$) with a given radial velocity $V_{r2} = 310\text{ m/s}$ ($f_{D2} \approx 8.266\text{ kHz}$). Before constructing the cross-correlation functions, the Doppler shifts f_{D1} and f_{D2} were previously compensated using a compensation scheme (see Fig. 3).

In Figures 6 and 7, two peaks are clearly visible, meaning that both objects were detected with corresponding delays.

Figure 8 shows that at $\text{SNR} = -29\text{ dB}$ one peak disappeared due to an error in the Doppler frequency spectrum estimation algorithm. One of the Doppler shifts was not detected correctly, and therefore compensated, which led to the disappearance of the second CCF peak. Only one peak is clearly visible,

which corresponds to the first object, i.e. the second object was not detected.

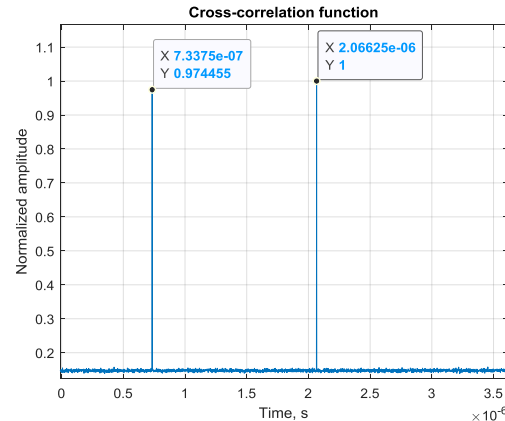


Fig. 6. Cross-correlation function in the presence of noise with a Gaussian distribution $\sigma=1$, $\text{SNR} = -3\text{ dB}$

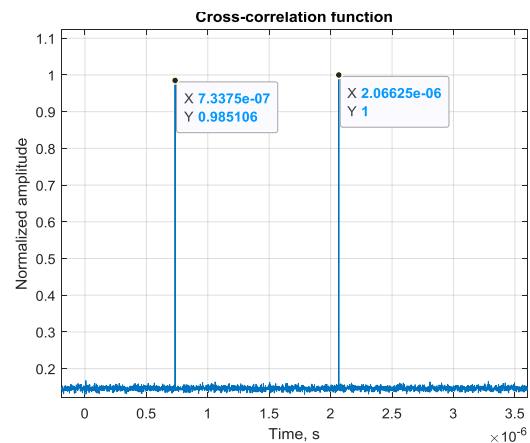


Fig. 7. Cross-correlation function in the presence of noise with a Gaussian distribution $\sigma=2.2$, $\text{SNR} = -10\text{ dB}$

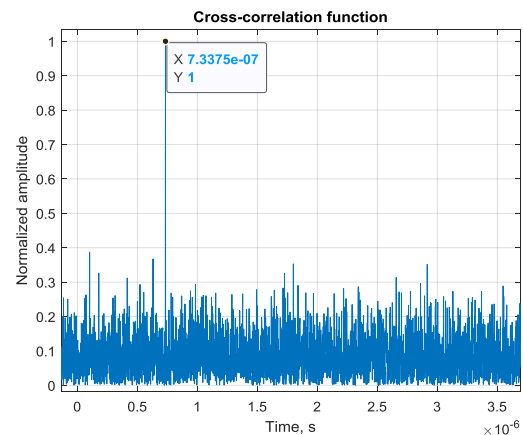


Fig. 8. Cross-correlation function in the presence of noise with a Gaussian distribution $\sigma=20$, $\text{SNR} = -29\text{ dB}$

Graphs 9-11 show the results of the simulation in the presence of two other objects located very close to each other: the third object at a given distance $D_3 = 215\text{ m}$ ($\tau \approx 1.4333\text{ }\mu\text{s}$) with a given radial

velocity $V_{r_3} = 110$ m/s ($f_{D_3} \approx 2.933$ kHz); the fourth object at a given distance $D_4 = 215,3750$ m ($\tau \approx 1.4358$ μ s) with a given radial velocity $V_{r_4} = 310$ m/s ($f_{D_4} \approx 8.266$ kHz). Before constructing the cross-correlation functions, the Doppler shifts f_{D_1} and f_{D_2} were previously compensated using a compensation scheme (see Fig. 3).

In Figures 9 and 10, two peaks are clearly visible, meaning that both objects were detected with corresponding delays.

Figure 11 shows that at SNR = -20 dB one peak disappeared due to an error in the Doppler frequency spectrum estimation algorithm. One of the Doppler shifts was not detected correctly, and therefore compensated, which led to the disappearance of the second CCF peak. Only one peak is clearly visible, which corresponds to the third object. The fourth object was not detected.

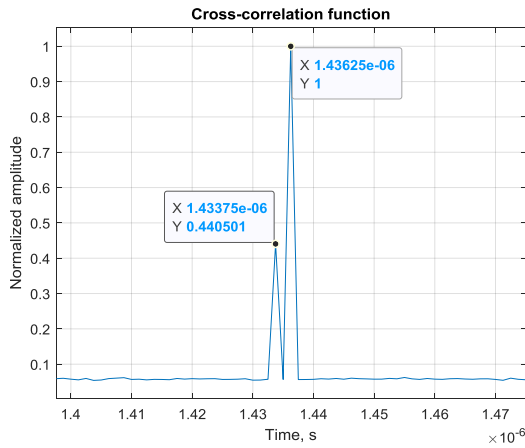


Fig. 9. Cross-correlation function in the presence of noise with a Gaussian distribution $\sigma=1$, SNR = -3 dB

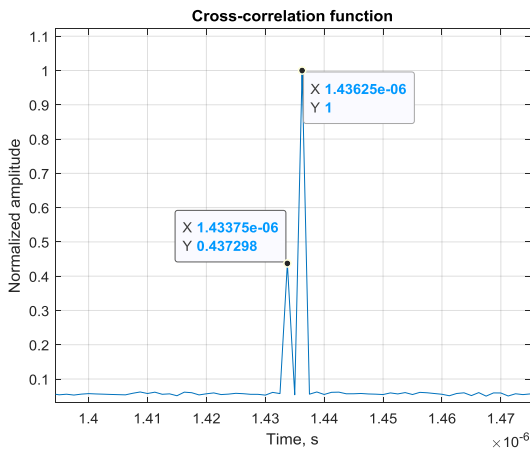


Fig. 10. Cross-correlation function in the presence of noise with a Gaussian distribution $\sigma=2.2$, SNR = -10 dB

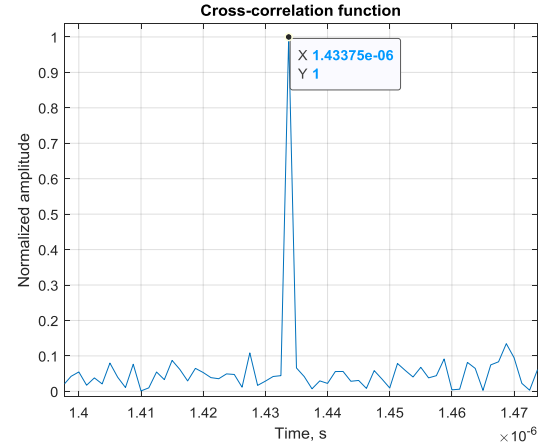


Fig. 11. Cross-correlation function in the presence of noise with a Gaussian distribution $\sigma=20$, SNR = -29 dB

Thus, for correct detection of all targets in the presence of white noise, it is necessary that the signal to noise ratio be greater than SNR = -29 dB.

During the operation of radio rangefinders in difficult conditions, their signal undergoes significant distortions due to reflections from the underlying surface, which mostly have a pronounced non-Gaussian nature. One of the options for mathematically describing such scattering, in particular in cases of reflections from turbulent sea areas, is the K-distribution model [15].

From a physical point of view, this distribution characterizes the processes of reflection of electromagnetic radiation from environments with multi-level spatial geometry (for example, a stormy sea). The basis of this model is the concept of composite scattering, which considers the resulting signal as a superposition of two independent phenomena, namely: fast fluctuations (speckle noise), which arise due to the interference of waves from a large number of small local reflectors located within one resolution element; slow fluctuations (modulation process), which are caused by macroscopic changes in the effective scattering area of the surface itself (for example, the presence of large waves or changes in the relief) (the gamma distribution is used for description).

The K-distribution, due to the mixing of these two factors, is formed as a Gaussian distribution, in which the standard deviation is distributed according to the gamma law:

$$x[n] = z[n] \cdot g[n], \quad (8)$$

where $x[n]$ is the K-noise count; $z[n]$ is the texture component, modeled as the root of a random variable $v[n]$, which has a Gamma distribution:

$z[n] = \sqrt{\nu[n]}$; $g[n]$ – is the speckle component, which is Gaussian noise with zero expectation and unit variance.

Figures 12–14 show histograms of K-distributed noise for different values of the shape parameter ν .

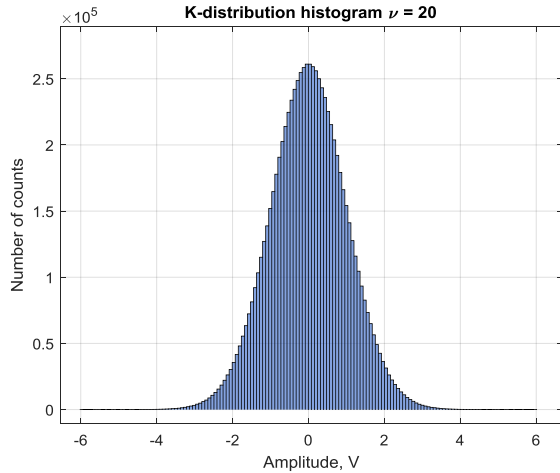


Fig. 12. K-distribution histogram $\nu=20$

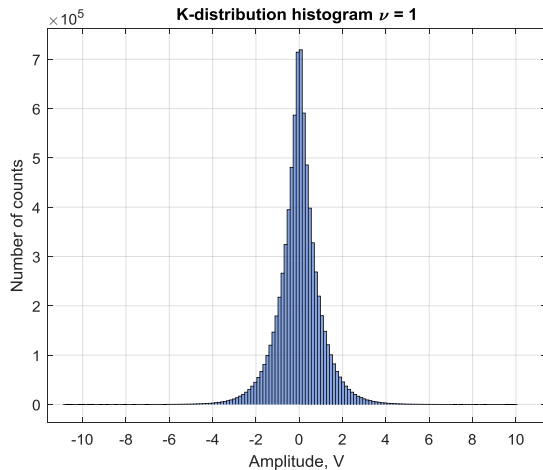


Fig. 13. K-distribution histogram $\nu=1$

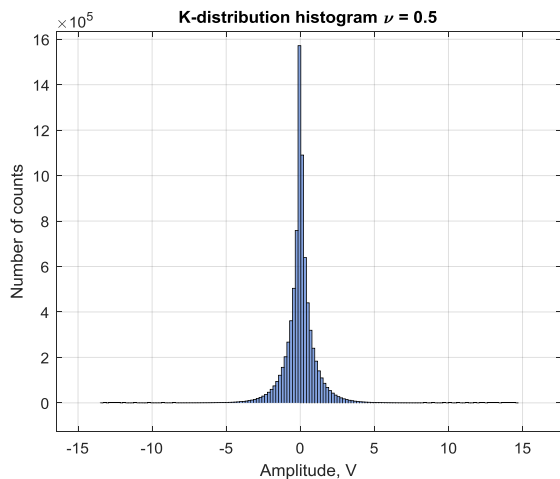


Fig. 14. K-distribution histogram $\nu=0.5$

It can be seen from histograms 12–14 that the smaller the value of ν , the longer the “tails” of the histogram. Physically, this means that the probability of large-amplitude pulses increases with decreasing shape parameter ν .

Figures 15–20 shows the cross-correlation functions in the presence of noise with K-distribution with different values of the scale parameter μ and, accordingly, with different signal-to-noise ratios. Graphs 15–17 show the results of the simulation in the presence of two objects: the first object at a given distance $D_1 = 110$ m ($\tau \approx 0.733$ μ s) with a given radial velocity $V_{r_1} = 110$ m/s ($f_{D_1} \approx 2.933$ kHz); the second object at a given distance $D_2 = 310$ m ($\tau \approx 2.07$ μ s) with a given radial velocity $V_{r_2} = 310$ m/s ($f_{D_2} \approx 8.266$ kHz). Before constructing the cross-correlation functions, the Doppler shifts f_{D_1} and f_{D_2} were previously compensated using a compensation scheme (see Fig. 3).

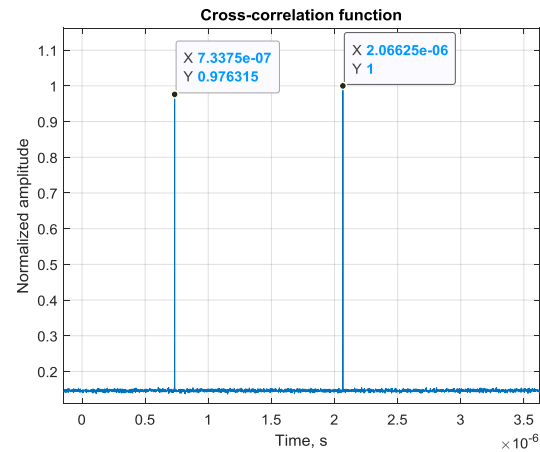


Fig. 15. Cross-correlation function in the presence of noise with K-distribution $\nu=0.5$, $\mu=1$, SNR = – 3 dB

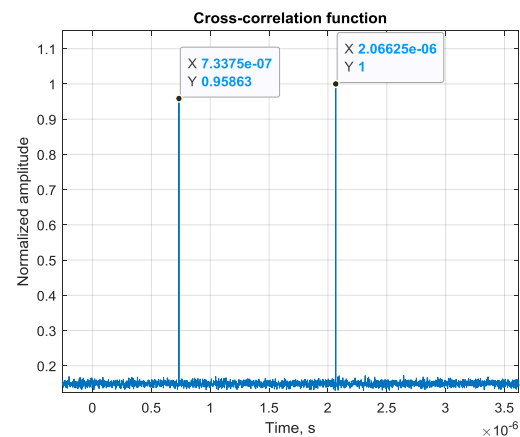


Fig. 16. Cross-correlation function in the presence of noise with K-distribution $\nu=0.1$, $\mu=10$, SNR = – 13 dB

In Figures 15 and 16, two peaks are clearly visible, meaning that both objects were detected with corresponding delays.

Figure 17 shows that at $\text{SNR} = -27.5$ dB one peak disappeared due to an error in the Doppler frequency spectrum estimation algorithm. One of the Doppler shifts was not detected correctly, and therefore compensated, which led to the disappearance of the second CCF peak. Only one peak is clearly visible, which corresponds to the first object, i.e. the second object was not detected.

Graphs 18–20 show the results of the simulation in the presence of two other objects located very close to each other: the third object at a given distance $D_3 = 215$ m ($\tau \approx 1.4333 \mu\text{s}$) with a given radial velocity $V_{r_3} = 110$ m/s ($f_{D_3} \approx 2.933$ kHz); the fourth object at a given distance $D_4 = 215,3750$ m ($\tau \approx 1.4358 \mu\text{s}$) with a given radial velocity $V_{r_4} = 310$ m/s ($f_{D_4} \approx 8.266$ kHz). Before constructing the cross-correlation functions, the Doppler shifts f_{D_1} and f_{D_2} were previously compensated using a compensation scheme (see Fig. 3).

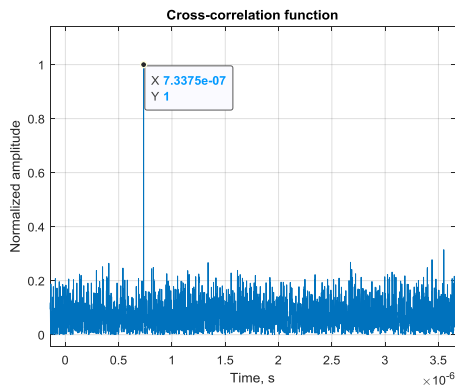


Fig. 17. Cross-correlation function in the presence of noise with K-distribution $\nu=0.5$, $\mu=280$, $\text{SNR} = -27.5$ dB

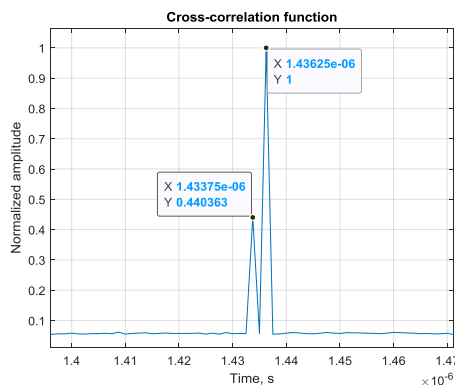


Fig. 18. Cross-correlation function in the presence of noise with K-distribution $\nu=20$, $\mu=1$, $\text{SNR} = -3$ dB

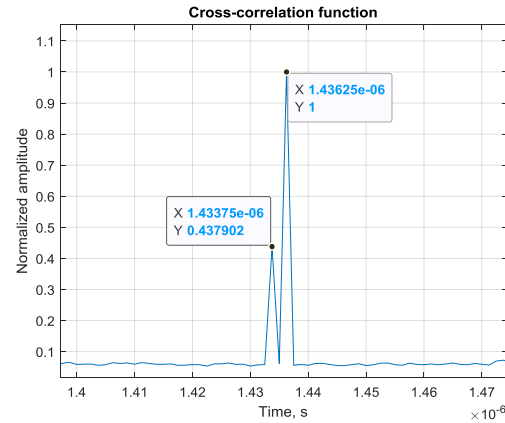


Fig. 19. Cross-correlation function in the presence of noise with K-distribution $\nu=0.5$, $\mu=10$, $\text{SNR} = -13$ dB

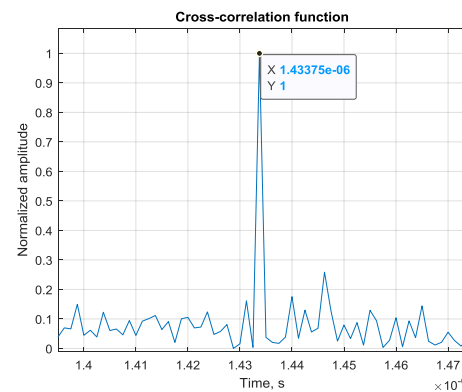


Fig. 20. Cross-correlation function in the presence of noise with K-distribution $\nu=0.5$, $\mu=280$, $\text{SNR} = -27.5$ dB

In Figures 18 and 19, two peaks are clearly visible, meaning that both objects were detected with corresponding delays.

Figure 20 shows that at $\text{SNR} = -27.5$ dB one peak disappeared due to an error in the Doppler frequency spectrum estimation algorithm. One of the Doppler shifts was not detected correctly, and therefore compensated, which led to the disappearance of the second CCF peak. Only one peak is clearly visible, which corresponds to the third object, i.e. the fourth object was not detected.

Thus, for correct detection of all targets in the presence of K-distribution noise, it is necessary that the signal/noise ratio be greater than $\text{SNR} = -27.5$ dB.

Impulse noise is a type of interference that consists of individual short-duration pulses of large amplitude that occur randomly in time and are superimposed on the desired signal. Sources of such noise are industrial devices and equipment, electrical discharges, pulsed power supplies, communication equipment, electronic switching devices, natural phenomena (lightning, solar activity), etc. [17]. One

of the options for mathematical description of impulse noise is the Laplace distribution:

$$f(x) = \frac{1}{\sigma\sqrt{2}} \exp\left(-\frac{\sqrt{2}|x-\mu|}{\sigma}\right). \quad (9)$$

In equation (9), σ is the standard deviation, μ is the mathematical expectation.

Figures 21–26 shows the cross-correlation functions in the presence of background Gaussian noise ($\mu=0, \sigma=1$) and impulse noise with a Laplace distribution ($\mu=0, P=0.1$ – probability of pulse occurrence) for different values of the standard deviation (σ).

Graphs 21–23 show the results of the simulation in the presence of two objects: the first object at a given distance $D_1 = 110$ m ($\tau \approx 0.733 \mu\text{s}$) with a given radial velocity $V_{r_1} = 110$ m/s ($f_{D_1} \approx 2.933$ kHz); the second object at a given distance $D_2 = 310$ m ($\tau \approx 2.07 \mu\text{s}$) with a given radial velocity $V_{r_2} = 310$ m/s ($f_{D_2} \approx 8.266$ kHz). Before constructing the cross-correlation functions, the Doppler shifts f_{D_1} and f_{D_2} were previously compensated using a compensation scheme (see Fig. 3).

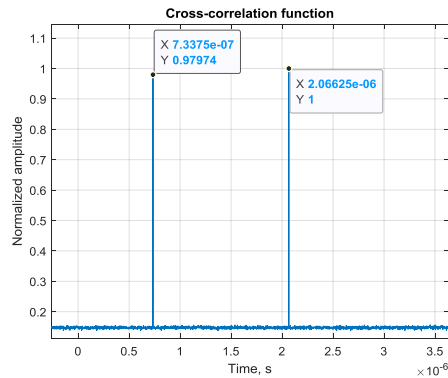


Fig. 21. Cross-correlation function in the presence of impulse noise $\sigma=1$, $\text{SNR} = -3.4$ dB

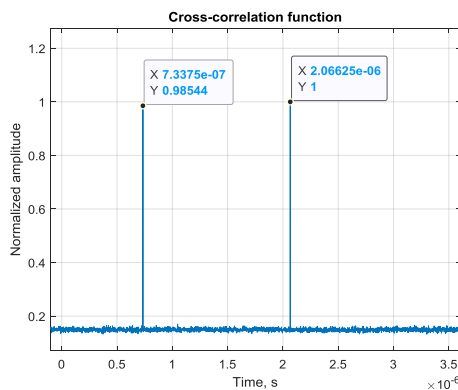


Fig. 22. Cross-correlation function in the presence of impulse noise $\sigma=7$, $\text{SNR} = -10.7$ dB

In Figures 21 and 22, two peaks are clearly visible, meaning that both objects were detected with corresponding delays.

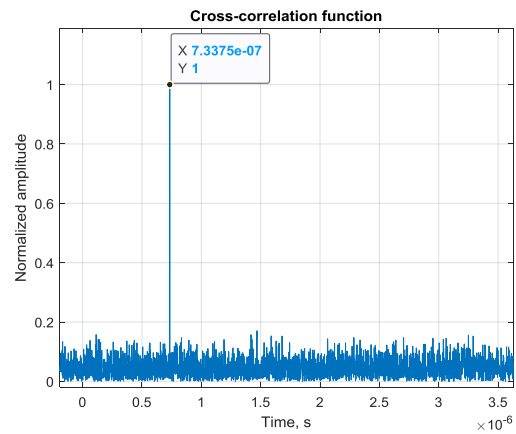


Fig. 23. Cross-correlation function in the presence of impulse noise $\sigma=26$, $\text{SNR} = -21.3$ dB

Figure 23 shows that at $\text{SNR} = -21.3$ dB one peak disappeared. One of the Doppler shifts was not detected correctly, and therefore compensated, which led to the disappearance of the second peak of the CCF. Only one peak is clearly visible, which corresponds to the first object, i.e. the second object was not detected.

Graphs 24–26 show the simulation results in the presence of two other objects located very close to each other: the third object at a given distance $D_3 = 215$ m ($\tau \approx 1.4333 \mu\text{s}$) with a given radial velocity $V_{r_3} = 110$ m/s ($f_{D_3} \approx 2.933$ kHz); the fourth object at a given distance $D_4 = 215.3750$ m ($\tau \approx 1.4358 \mu\text{s}$) with a given radial velocity $V_{r_4} = 310$ m/s ($f_{D_4} \approx 8.266$ kHz). Before constructing the cross-correlation functions, the Doppler shifts f_{D_1} and f_{D_2} were previously compensated using a compensation scheme (see Fig. 3).

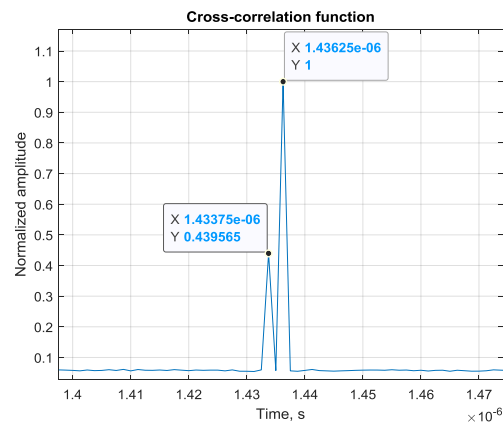


Fig. 24. Cross-correlation function in the presence of impulse noise $\sigma=1$, $\text{SNR} = -3.4$ dB

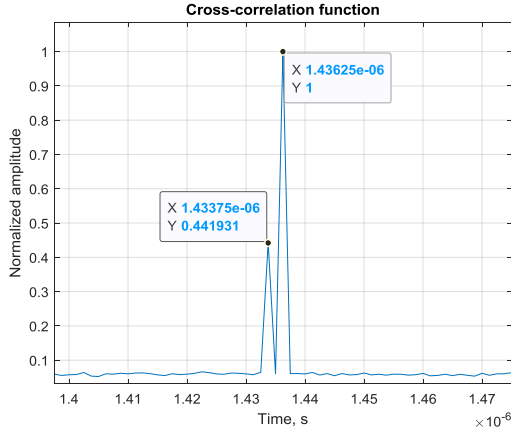


Fig. 25. Cross-correlation function in the presence of impulse noise $\sigma=7$, SNR = -10.7 dB

In Figures 24 and 25, two peaks are clearly visible, meaning that both objects were detected with corresponding delays.

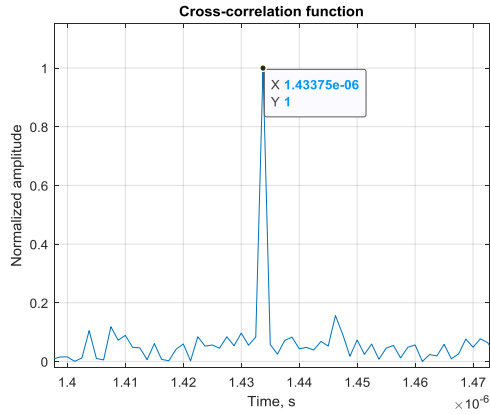


Fig. 26. Cross-correlation function in the presence of impulse noise $\sigma=26$, SNR = -21.3 dB

Figure 26 shows that at SNR = -21.3 dB one peak disappeared. One of the Doppler shifts was not detected correctly, and therefore compensated, which led to the disappearance of the second peak of the CCF. Only one peak is clearly visible, which corresponds to the third object, i.e. the fourth object was not detected.

Thus, for correct detection of all targets in the presence of a mixture of white and impulse noise, it is necessary that the signal/noise ratio be greater than SNR = -21.3 dB.

Therefore, peaks corresponding to different objects can be clearly separated from each other even under the influence of interference, provided that the signal-to-noise ratio is greater than -29 dB for white noise, greater than -27.5 dB for K-distribution noise, and greater than -21.3 dB for a mixture of white and impulse noise.

Graphs 6–26 were constructed based on the corresponding data from the simulation of the radio rangefinder operation (Fig. 5) in the MATLAB environment.

According to the modeling results, the distance to the first object is $D_{m_1} = 110.0625$ m; the distance to the second object is $D_{m_2} = 309.9375$ m; the distance to the third object is $D_{m_3} = 215.0625$ m; the distance to the fourth object is $D_{m_4} = 215.4375$ m.

Thus, the measurement errors are:

$$\Delta D_1 = |D_1 - D_{m_1}| = 0.0625 \text{ m}, \quad (10)$$

$$\Delta D_2 = |D_2 - D_{m_2}| = 0.0625 \text{ m}, \quad (11)$$

$$\Delta D_3 = |D_3 - D_{m_3}| = 0.0625 \text{ m}, \quad (12)$$

$$\Delta D_4 = |D_4 - D_{m_4}| = 0.0625 \text{ m}. \quad (13)$$

From Figures 9–10, 18–19 and 24–25 the resolution is:

$$D_p = |D_{m_4} - D_{m_3}| = 0.375 \text{ m}. \quad (14)$$

VI. CONCLUSIONS

This study reveals the principles of construction and algorithmic basis of a radio rangefinder that uses cross-correlation processing of broadband pulses with a noise-like structure. The features of the applied probing signals together with the corresponding processing algorithms allow to clearly fix the peaks of the cross-correlation function, which determines the high accuracy of distance determination.

The effectiveness of the developed system was tested using computer simulation under the influence of white noise, a mixture of white and impulse noise, and noise with a K-distribution. From the experimental data and graphical results, the signal-to-noise ratios necessary for the correct operation of the system were determined, namely more than -29 dB for white noise, more than -27.5 dB for noise with a K-distribution, and more than -21.3 dB for a mixture of white and impulse noise. The measurement error, which is 0.0625 m and the resolution, which is 0.375 m.

The general conclusion is that the combination of noise-like signals with correlation processing methods forms the foundation for designing radio rangefinders with high noise immunity and measurement accuracy. The introduction of such innovations into modern navigation equipment can be a step towards increasing the level of safety and overall efficiency of spatial positioning systems.

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О. І. Ільїн, К. І. Прокопенко, Дослідження ефективності радіодалекоміра з кореляційною обробкою в умовах дій негаусівських імпульсних завад

У статті досліджується робота радіодалекоміра з кореляційною обробкою широкосмугового сигналу в умовах дій завад різного типу. Розглянуто структурну модель радіодалекоміра та розкрито ключові механізми його роботи. Окремо розглянуто процедури обчислення часу затримки сигналу та інтеграцію контуру доплерівської компенсації, використання якого є обов'язковою умовою для запобігання деградації (розмиття) кореляційного максимуму при русі об'єкта. Роботу структурної моделі радіодалекоміра промодельовано в середовищі MATLAB в умовах впливу білого гаусівського шуму, імпульсного шуму з розподілом Лапласа та негаусівських завад із К-розподілом, що характерні для відбиттів від підстилаючої поверхні. В результаті дослідження визначено граничні значення відношення сигнал / шум, за яких система здатна коректно розрізняти об'єкти: не менше –29 дБ для білого шуму, –27,5 дБ для шуму з К-розподілом та –21,3 дБ для суміші білого та імпульсного шумів. Крім того, результати симуляції підтвердили високу точність системи: похибка вимірювання дальності становить 0,0625 м, а роздільна здатність сягає 0,4125 м. Отримані результати доводять доцільність використання запропонованого підходу для стабільної навігації безпілотних та пілотованих апаратів у складних завадових умовах.

Ключові слова: радіолокаційна система, радіотехнічна система, вимірювання, кореляція, обробка сигналу, аеронавігаційна система, радіоелектронна система, завади, К-розподіл.

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