

Igor Prokopenko, Eng.Sc.Doctor, Professor.
National University “Kyiv Aviation Institute”
<https://orcid.org/0000-0003-4169-3774>
email: ihor.prokopenko@npp.kai.edu.ua

Oleksandr Ilin, Postgraduate Student
National University “Kyiv Aviation Institute”
<https://orcid.org/0000-0002-9025-8915>
email: 5196906@stud.kai.edu.ua

ANALYSIS OF THE OPERATION OF A CORRELATION RANGE METER AGAINST NON-GAUSSIAN INTERFERENCE WITH K-DISTRIBUTION

Introduction

Modern aviation navigation and automatic flight control systems for both manned and unmanned aircraft critically depend on highly accurate altitude and distance data. Radio rangefinders are a fundamental component of these measurement systems [1, 2].

Problem statement

For safe and accurate execution of maneuvers at low altitudes – during automatic landing, terrain avoidance, or navigation in complex urban conditions – it is required to minimize the error in range measurement. Any inaccuracies at these stages can lead to catastrophic consequences, therefore, increasing the accuracy of radar measurements is a key factor in reducing risks and increasing overall flight safety [2, 3].

A special problem is the operation of radio rangefinders in harsh real-world operating conditions. The useful signal is distorted not only by intense thermal noise, multi-beam propagation of radio waves, and the growing influence of active intentional interference (EW devices), but also by intense reflections from the underlying surface. In such situations, the noise background acquires a pronounced non-Gaussian character, for the adequate statistical description of which (in particular, when modeling reflections from the sea surface), the K-distribution is actively used. Classical methods of reception, calculated on Gaussian noise, lose their effectiveness in such conditions, which causes critical errors in range estimation [4].

In addition, today in radar, intelligent data processing methods based on deep neural networks are rapidly developing [7]. The effective operation of machine learning algorithms (for example, for target recognition or compensation of complex nonlinear interference) in the architecture of peripheral computing is possible only if the quality of the initial signal

processing is high [8]. Errors made at the stage of basic measurement significantly reduce the effectiveness of subsequent neural network filtering and make the use of such intelligent systems impractical.

Thus, there is an urgent scientific and technical need to develop and improve computationally efficient methods for processing radar signals based on the theory of optimal correlation reception (taking into account non-Gaussian interference models) in order to maximize the accuracy of range measurement in modern radio rangefinders.

Review of latest articles

Studies [9–17] consider the use of correlation processing and broadband signals in radar. The authors of these publications emphasize that such principles of signal formation and processing are a promising direction for the development of radar.

In works [9–12] it is stated that the application of correlation processing to broadband sounding signals can significantly increase the spatial resolution and accuracy of measuring the distance to objects. Accordingly, such advantages open up broad prospects for the development of new radar complexes with improved parameters.

Objectives of the article

The purpose of the article is to analyze the noise immunity of a correlation radio rangefinder with a broadband sounding signal against the background of K-distributed interference. To achieve the goal, the following tasks are solved in the work: consideration of the structural diagram of the radio rangefinder and explanation of the basic principles of its operation; computer modeling of the system in the presence of K-distributed interference to assess its noise immunity.

Presentation of the main material

Basic principles of radar measurements

The operation of radio rangefinders is based on the basic laws of electrodynamics, in particular, on the

ability of electromagnetic waves to reflect from physical bodies and propagate in space in a straight line at a constant speed. This property allows using radio waves as a tool for non-contact determination of spatial coordinates of objects. Determining the radial velocity of an object is based on the Doppler effect [18].

To calculate the range to an object and its radial velocity, it is necessary to measure the reflected signal delay τ and the Doppler frequency shift f_D , respectively.

Method description

According to the results of research [9–12], the use of broadband signals with their correlation processing is an effective method for increasing the resolution and accuracy of distance measurement. The hardware implementation of this concept in the form of a structural diagram of a radio rangefinder is shown in Fig. 2. This illustration details the entire signal path: from the moment of its formation to the final calculation of the distance. In Fig. 2, the transmitting antenna is designated as A1, the receiving antenna as A2, the power amplifier as PA, the phase modulator as FM, the high-frequency generator as HFG, the linear path as LP, the multiplier is designated by the symbol "X", the integrator is designated by the symbol "J", the peak meter as M, the range calculation unit as D.

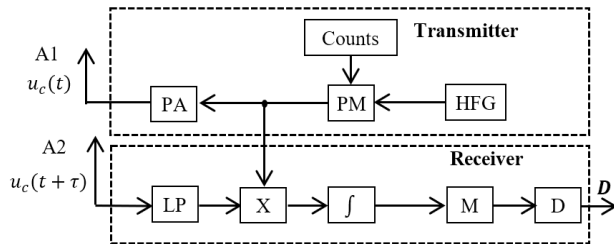


Fig. 2. Structural diagram of a correlation meter

The basis of the system is the use of a complex probing signal with noise-like phase modulation. The formation process occurs as follows: a high-frequency generator (HFG) creates a basic harmonic oscillation with a carrier frequency f_{c0} . The signal passes through a phase modulator (PM), where its phase changes according to the law of a pseudo-random sequence – an array of samples p . Analytically, such a signal is described by the equation:

$$u_c(t) = U_{c0} \cdot \sin(2\pi \cdot f_{c0}t + \beta_0 p_t),$$

where U_{c0} – is the amplitude; $\beta_0 = 1$ – is the modulation index; p_t – is a random sample from the array p at time t . The spectrum of the probing signal with a carrier frequency $f_{c0} = 4$ GHz is presented in Fig. 3.

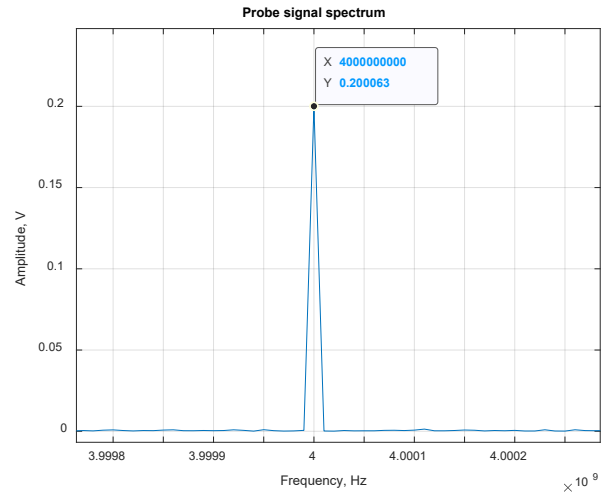


Fig. 3. Probe signal spectrum

After formation, the signal is amplified by a power amplifier (PA) and radiated into space through the transmitting antenna (A1). Reflected from the observation object, the electromagnetic wave returns to the radio rangefinder and is captured by the receiving antenna (A2).

The reflected signal undergoes a time delay τ and acquires a Doppler frequency shift f_D (if the target is moving), which is described by the expression:

$$u_c(t + \tau) = U_c \cdot \sin(2\pi \cdot (f_{c0} + f_D) \cdot (t + \tau) + \beta_0 p_{t+\tau}),$$

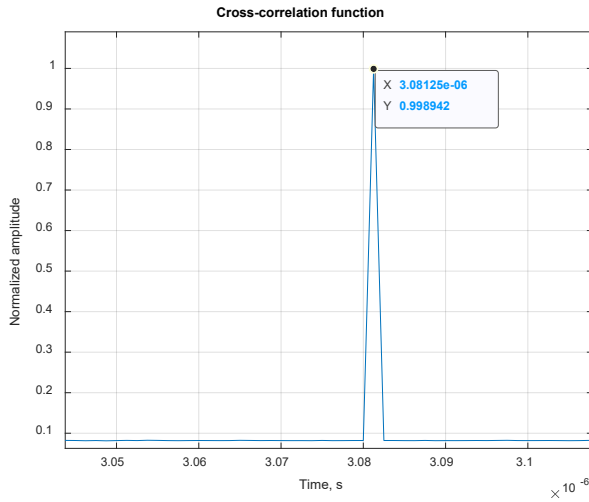
where U_c – is the amplitude of the signal reflected from the object; τ – is the time delay of the signal; f_D – is the Doppler frequency shift; $p_{t+\tau}$ – is a random sample from the array p at time $t + \tau$.

After passing through the linear path of the receiver (LP), the received signal enters the multiplier, where it is mixed with the reference (probe) signal $u_c(t)$. Next, the integrator calculates the cross-correlation function (CCF) of these two signals:

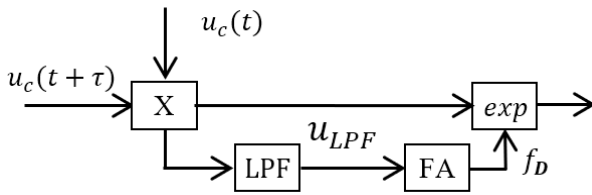
$$g(\tau) = \int_{-\infty}^{\infty} u_c(t) \cdot u_c(t + \tau) dt.$$

For a stationary target (when $f_D = 0$) on the graph of the cross-correlation function (Fig. 4) a clearly pronounced peak is formed at the point corresponding to the delay time τ . The peak meter (M) records this value and transmits it to the block D for calculating the exact range.

If the target has a radial velocity, a Doppler frequency shift ($f_D \neq 0$), occurs, which critically affects the operation of the system. Even small shifts lead to blurring and loss of clarity of the peak of the cross-correlation function. This makes direct measurement of the delay impossible [12].

Fig. 4. Cross-correlation function $g(\tau)$

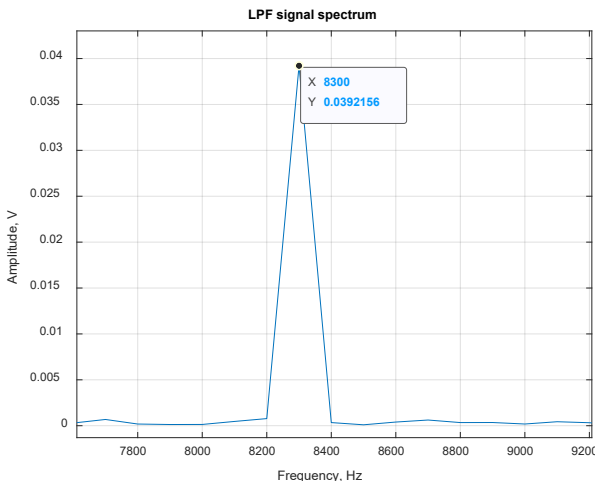
To eliminate this problem, the Doppler shift compensation circuit is used in Fig. (5) [12]. In this figure, the low-pass filter is designated as LPF, the frequency analyzer as FA, and the exponential multiplication block is designated by the symbols “exp”.

Fig. 5. Compensation scheme of f_D

The signal from the multiplier is passed through a low-pass filter (LPF). The LPF extracts a low-frequency information component with amplitude U_{LPF} :

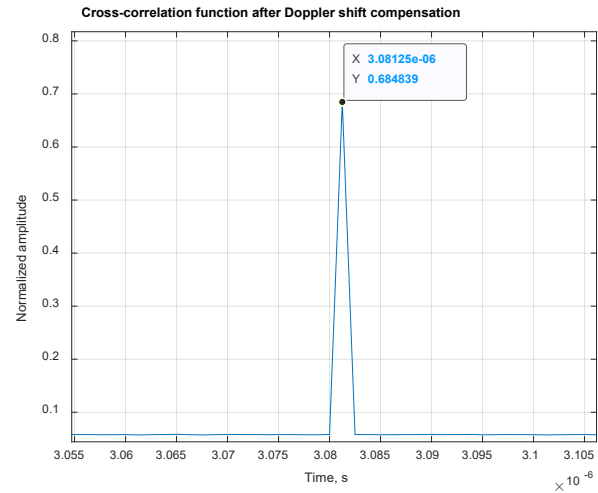
$$u_{LPF}(t + \tau) = U_{LPF} \cdot \cos(-2\pi f_D t - 2\pi(f_{c0} + f_D)\tau + \beta_0(p_t - p_{t+\tau})).$$

The spectrum of the signal $u_{LPF}(t + \tau)$ is presented in Fig. 6; the Doppler shift is $f_D = 8300$ Hz.

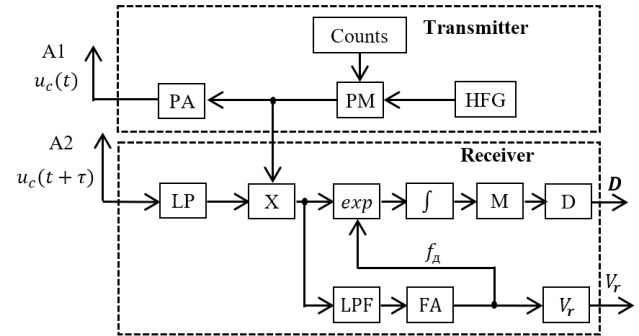
Fig. 6. Signal spectrum u_{LPF}

The frequency analyzer (FA) evaluates the spectrum of this signal and accurately determines the value of the Doppler frequency f_D . Knowing f_D , the system performs phase correction: the signal is multiplied by the exponent $e^{-j2\pi f_D t}$. This eliminates the influence of the object's velocity, allowing the integrator to form a clear CCF peak for calculating the range. In addition, the measured Doppler shift is used in parallel by the V_r (Fig. 8) to calculate the radial velocity of the target.

The CCF with Doppler shift compensation $f_D = 8300$ Hz is shown in Fig. 7.

Fig. 7. Cross-correlation function after f_D compensation

The scheme of a radio rangefinder that implements the shift compensation function is shown in Fig. 8.

Fig. 8. Structural diagram of a correlation meter with f_D compensation

If the rangefinder is built on the basis of digital processing, its accuracy directly depends on the signal sampling frequency. The smaller the sampling step Δt_s , the higher the accuracy and resolution of the measurement. For example, with a sampling step $\Delta t_s = 1,25$ ns the distance determination error is:

$$\Delta D = \frac{c \cdot \Delta t_s}{4} = 0,09375 \text{ m.}$$

Impact of noise on system operation

In today's harsh operating conditions of radio rangefinders, the useful signal is distorted by intense reflections from the underlying surface, which often acquire a pronounced non-Gaussian character. One of

the recognized models for describing complex scattering, particularly from rough sea surfaces, is the K-distribution [19].

Physically, the K-distribution describes the processes of scattering of electromagnetic waves on surfaces with a complex, multi-scale spatial structure.

The model is based on the concept of complex (composite) scattering, which is considered as a superposition of two independent processes:

- Fast fluctuations (speckle noise) – caused by the interference of waves reflected from a large number of small local scatterers within a single resolution element. This component traditionally has Rayleigh statistics.

- Slow fluctuations (modulation process) – reflect large-scale changes in the effective scattering area (ESA) of the surface itself (e.g., large sea waves). This component is usually described by a gamma distribution.

The mixture of these two processes (Rayleigh scattering, the dispersion of which is randomly modulated according to the gamma law) forms the resulting K-distribution.

The probability density function (PDF) of the K-distribution has the following form [20]:

$$f(x; \mu; \nu; L) = \frac{2}{x} \left(\frac{L\nu x}{\mu} \right)^{\frac{L+\nu}{2}} \frac{1}{\Gamma(L)\Gamma(\nu)} K_{\nu-L} \left(2\sqrt{\frac{L\nu x}{\mu}} \right),$$

where $\Gamma(\cdot)$ – Gamma function; $K_{\nu-L}(\cdot)$ – modified Bessel function of the second kind of order $\nu - L$; ν – shape parameter, on which the “sharpness” of the distribution depends: the smaller ν , the heavier the “pointedness” of the distribution; μ – scale parameter; L – speckle shape parameter.

Fig. 9–11 shows the probability density functions (PDF) of the K-distribution for different values of the shape parameter ν , scale parameter μ and speckle shape parameter L .

Fig. 12–21 shows the signal spectra at the output of the low-pass filter and the cross-correlation functions in the presence of noise with a K-distribution with different values of the shape parameter ν . The signal-to-noise ratio in all cases is $SNR = -3$ dB.

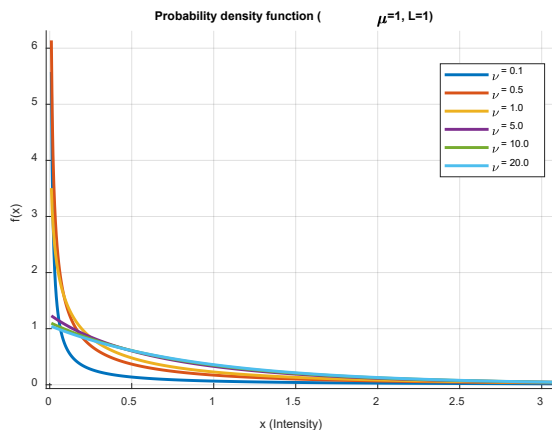


Fig. 9. PDF of K-distribution for different values of ν

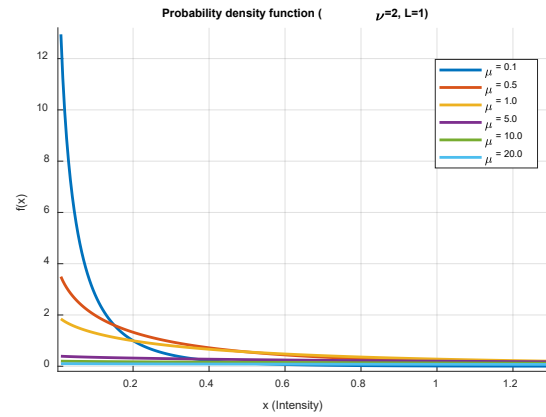


Fig. 10. PDF of K-distribution for different values of μ

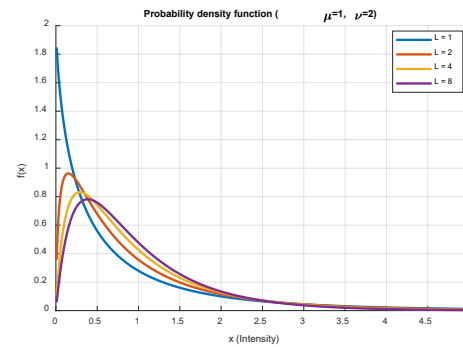


Fig. 11. PDF of K-distribution for different values of L

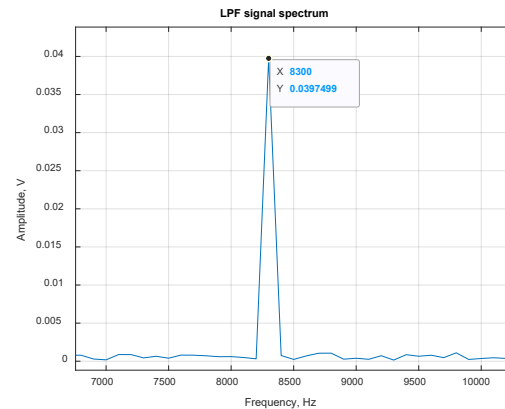


Fig. 12. Signal spectrum at the output of the low-pass filter in the presence of noise with K-distribution $\nu = 0.1$, $\mu = 1$, $L = 1$

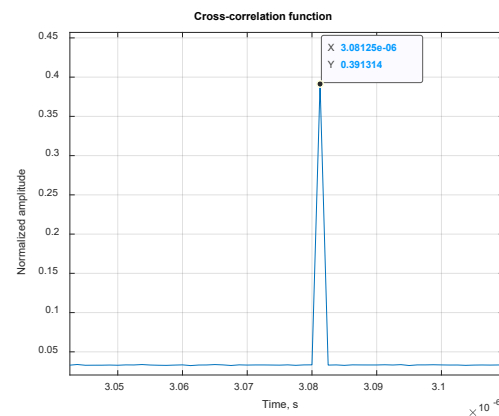


Fig. 13. Cross-correlation function in the presence of noise with K-distribution $\nu = 0.1$, $\mu = 1$, $L = 1$

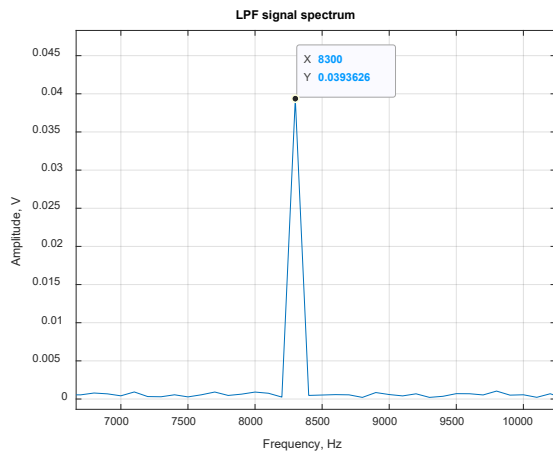


Fig. 14. Signal spectrum at the output of the low-pass filter in the presence of noise with K-distribution $\nu = 0.5$, $\mu = 1$, $L = 1$

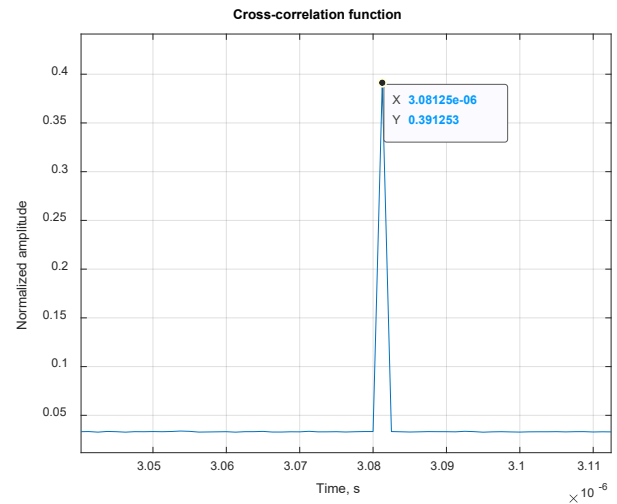


Fig. 17. Cross-correlation function in the presence of noise with K-distribution $\nu = 1$, $\mu = 1$, $L = 1$

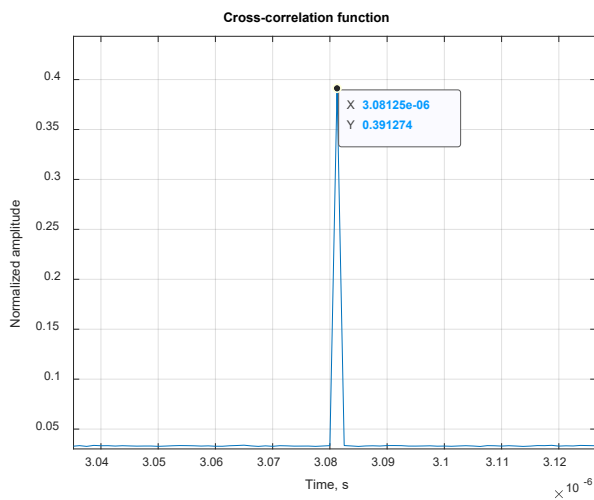


Fig. 15. Cross-correlation function in the presence of noise with K-distribution $\nu = 0.5$, $\mu = 1$, $L = 1$

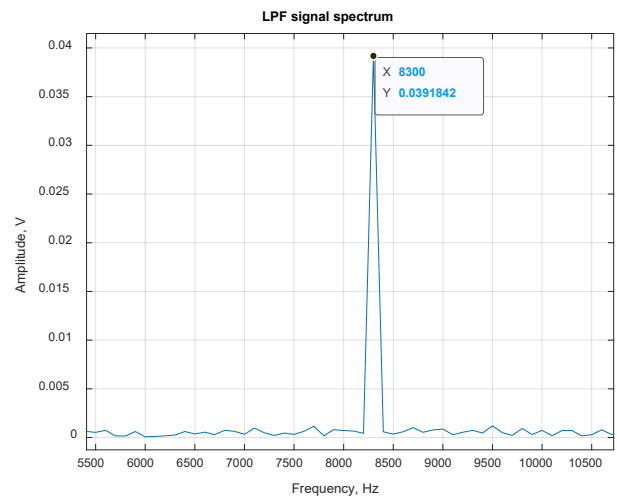


Fig. 18. Signal spectrum at the output of the low-pass filter in the presence of noise with K-distribution $\nu = 10$, $\mu = 1$, $L = 1$

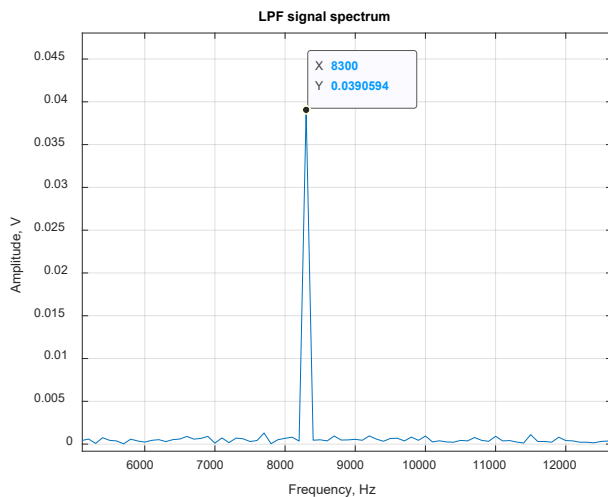


Fig. 16. Signal spectrum at the output of the low-pass filter in the presence of noise with K-distribution $\nu = 1$, $\mu = 1$, $L = 1$

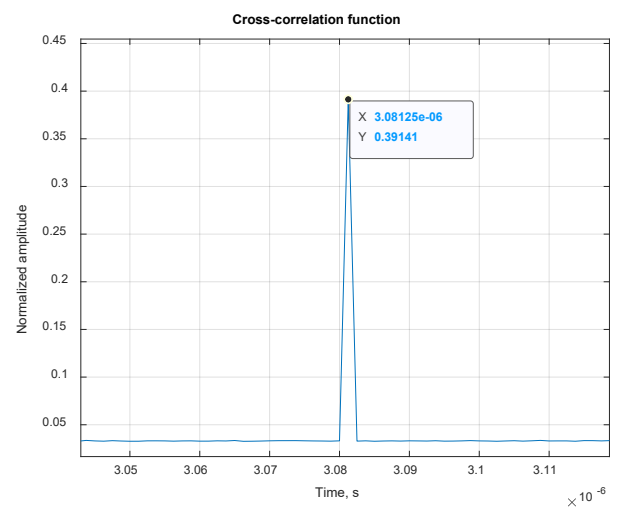


Fig. 19. Cross-correlation function in the presence of noise with K-distribution $\nu = 10$, $\mu = 1$, $L = 1$

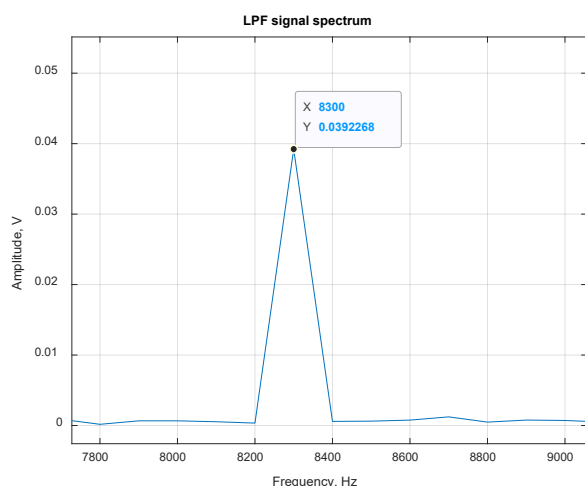


Fig. 20. Signal spectrum at the output of the low-pass filter in the presence of noise with K-distribution $\nu = 20$, $\mu = 1$, $L = 1$

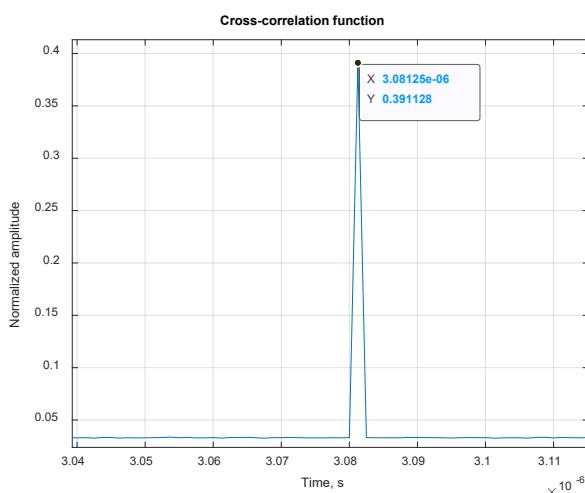


Fig. 21. Cross-correlation function in the presence of noise with K-distribution $\nu = 20$, $\mu = 1$, $L = 1$

As can be seen from Fig. 12-21, the peaks are clear even against the background of interference.

Conclusions

The paper describes the architecture and algorithm of the radio rangefinder, the operation of which is based on the correlation analysis of broadband signals with noise-like modulation. The specificity of such a probing pulse and its processing methods guarantee reliable identification of the maxima of the cross-correlation function, which is a direct indication of the high accuracy of the measurements.

It is noted that the location of targets with significant radial velocity requires mandatory leveling of the Doppler frequency shift. The structural diagram of the algorithm for compensating for this shift is demonstrated.

The behavior of the system under the influence of K-distributed interference was investigated by computer modeling. The obtained graphical data (Fig. 12–21) confirm the ability of the device to confidently isolate

the useful signal (spectral and correlation peaks) even in the presence of strong background noise, proving its high noise immunity.

In conclusion, the use of noise-like signals in combination with correlation processing is a promising direction for creating the latest radio rangefinders with optimized accuracy and immunity to interference. The integration of these developments into modern navigation and rangefinder complexes will significantly increase the safety and efficiency of navigation systems.

REFERENCES

- [1] A. Soumya, C. Krishna Mohan, and L. R. Cenkeramaddi, "Recent Advances in mmWave-Radar-Based Sensing, Its Applications, and Machine Learning Techniques: A Review," *Sensors*, vol. 23, no. 21, p. 8901, 2023. <https://doi.org/10.3390/s23218901>.
- [2] Y. Jing, R. Sipahi, and J. Martinez-Lorenzo, "Synchronized Multi-Directional FMCW mmWave Radar-Inertial Odometry: Robust Positioning and Autonomous Navigation Experiments for UAVs in Low-Light Indoor Environments," *Drones*, vol. 10, no. 2, p. 120, 2026. <https://doi.org/10.3390/drones10020120>.
- [3] A. Sengupta, L. Cheng, and S. Cao, "Robust Multi-object Tracking Using mmWave Radar-Camera Sensor Fusion," *IEEE Sensors Letters*, vol. 6, no. 11, pp. 1–4, 2022. <https://doi.org/10.1109/LSSENS.2022.3213529>.
- [4] J. Gao, J. Du, and W. Wang, "Radar Detection of Fluctuating Targets under Heavy-Tailed Clutter Using Track-Before-Detect," *Sensors*, vol. 18, no. 7, Art. no. 2241, Jul. 2018. <https://doi.org/10.3390/s18072241>.
- [5] J. Lu, Y. Guo, W. Feng, X. Hu, J. Gong, and Y. Zhang, "Intelligent Recognition and Parameter Estimation of Radar Active Jamming Based on Oriented Object Detection," *Remote Sens.*, vol. 17, no. 15, p. 2646, 2025. <https://doi.org/10.3390/rs17152646>.
- [6] J. Liu, J. Ma, L. Shi, Z. Lin, Y. Kong, and J. Chen, "Jamming Recognition Based on Adaptive Feature Focusing Convolutional Neural Network For Agile Cognitive Radar," *Preprints.org*, 2026. <https://doi.org/10.20944/preprints202603.1908.v1>
- [7] E. Blasch, G. Chen, Y. Chen, A. Savakis, F. Daum, and L. Grewe, "Edge-based computing challenges and opportunities for sensor fusion: panel review," *Proc. SPIE*, vol. 13479, 2025. <https://doi.org/10.1117/12.3052850>.
- [8] S.-E. Tsai and C.-H. Hsieh, "Glare-Aware Resi-YOLO: Tiny Vessel Detection with Dual-Brain Edge Deployment for Maritime UAVs," *Preprints.org*, 2026. <https://doi.org/10.20944/preprints202602.1747.v1>
- [9] Ilin O.I, "Analysis of radar range measurement methods," in 2023 International Conference on Information and Telecommunication Technologies

- and Radio Electronics (UkrMiCo), Kyiv, Ukraine, 2023, pp. 171–176, doi: 10.1109/UkrMiCo61577.2023.10380370.
- [10] O. Ilin, I. Prokopenko, and V. Taran, "The Method of Distance Measurement Using a Broadband Noise-like Signal," in *2024 IEEE 7th International Conference on Actual Problems of Unmanned Aerial Vehicles Development (APUAVD)*, Kyiv, Ukraine, 2024, pp. 68–71, doi: 10.1109/APUAVD64488.2024.10765906.
- [11] I. Prokopenko and O. Ilin, "Improving Range Measurement Accuracy for Moving Targets," in *2025 IEEE 8th International Conference on Methods and Systems of Navigation and Motion Control (MSNMC)*, Kyiv, Ukraine, 2025, pp. 1–5, doi: 10.1109/MSNMC61130.2025.11399704.
- [12] І. Прокопенко, О. Ільїн. "Кореляційний радіодалекомір з шумоподібною модуляцією зондувального сигналу," *Наукоемні технології*, вип. 67, 2025, doi: 10.18372/2310-5461.67.20045.
- [13] X. Ouyang, S. Yao, and Q. Wan, "A Coherent Integrated TDOA Estimation Method for Target and Reference Signals," *Electronics*, vol. 11, no. 16, p. 2632, Aug. 2022, doi: 10.3390/electronics11162632.
- [14] Z. Xu, H. Tian, L. Zhang, Q. Zhao, Z. Zhang, S. Zhang, H. Li, and Y. Liu, "High-resolution radar ranging based on the ultra-wideband chaotic optoelectronic oscillator," *Optics Express*, vol. 31, no. 14, p. 22594, 2023, doi: 10.1364/OE.492329.
- [15] M. F. R. Al-Okby, S. Junginger, T. Roddelkopf, and K. Thurow, "UWB-Based Real-Time Indoor Positioning Systems: A Comprehensive Review," *Applied Sciences*, vol. 14, no. 23, p. 11005, 2024, doi: <https://doi.org/10.3390/app142311005>.
- [16] Y.-X. Zhang, R.-J. Hong, C.-F. Yang, Y.-J. Zhang, Z.-M. Deng, and S. Jin, "A Fast Motion Parameters Estimation Method Based on Cross-Correlation of Adjacent Echoes for Wideband LFM Radars," *Applied Sciences*, vol. 7, no. 5, p. 500, 2017, doi: <https://doi.org/10.3390/app7050500>.
- [17] J. Ninnemann, P. Schwarzbach, and O. Michler, "Toward UWB Impulse Radio Sensing: Fundamentals, Potentials, and Challenges," in *UWB Technology - New Insights and Developments*, London, UK: IntechOpen, 2023, doi: 10.5772/intechopen.110040.
- [18] M. A. Richards, J. A. Scheer, and W. A. Holm, Eds., *Principles of Modern Radar: Basic Principles*. Raleigh, NC, USA: SciTech Publishing, 2010. <https://doi.org/10.1049/SBRA021E>.
- [19] Jianda Xie, Mengjia Duan, Bingluo Zhao, Xiaojian Xu, "An empirical model for the shape parameter of K distribution in radar sea clutter at low grazing angles," *Proc. SPIE 13670, Artificial Intelligence and Image and Signal Processing for Remote Sensing XXXI*, 1367011 (28 October 2025). <https://doi.org/10.1117/12.3069819>.
- [20] N. J. Redding, "Estimating the Parameters of the K Distribution in the Intensity Domain," *Electronics and Surveillance Research Laboratory, Defence Science and Technology Organisation, Salisbury, SA, Australia, Tech. Rep. DSTO-TR-0839*, Jul. 1999.

Прокопенко І. Г., Ільїн О. І.

АНАЛІЗ РОБОТИ КОРЕЛЯЦІЙНОГО ВИМІРЮВАЧА ДАЛЬНОСТІ НА ТЛІ НЕГАУСІВСЬКИХ ЗАВАД З К-РОЗПОДІЛОМ

У даній статті аналізується завадостійкість кореляційного радіодалекоміра, який використовує широкопосмугові зондувальні сигнали із шумоподібною фазовою модуляцією, на тлі негаусівських завад, що описуються К-розподілом. Актуальність роботи зумовлена критичною потребою в безперервних і високоточних даних про дальність для систем навігації та управління пілотованих літальних апаратів і БПЛА в жорстких умовах експлуатації, зокрема під впливом інтенсивних відбиттів від підстилаючої поверхні. У таких ситуаціях завади набувають вираженого негаусівського характеру. Однією з визнаних моделей для опису складного розсіювання, є К-розподіл. У роботі наведено структурну схему радіодалекоміра та описано базові принципи його функціонування, включаючи алгоритми формування зондувального сигналу, обробки відбитого сигналу, вимірювання часу затримки та радіальної швидкості об'єкту. Наведені відповідні математичні формули. Представлені графік спектру зондувального сигналу та взаємкореляційної функції опорного та відбитого сигналів. Розглядається структурна схема контуру компенсації доплерівського зсуву частоти та принцип його роботи. Його функціонування є критично необхідним для усунення розмиття кореляційного піку під час руху цілі. Наведено формулу ЩРІ К-розподілу та його графіки для різних значень його параметрів. Основну увагу приділено комп'ютерному моделюванню роботи системи при наявності шуму з К-розподілом із різними значеннями параметра форми. Результати моделювання представлені у вигляді відповідних графіків взаємкореляційної функції та спектру сигналу, які доводять, що кореляційна обробка забезпечує чітке виділення максимумів взаємкореляційної функції навіть на тлі сильного фонового шуму. Відповідно, використання шумоподібних сигналів у поєднанні з кореляційною обробкою є перспективним напрямком для створення новітніх радіодалекомірів з оптимізованою точністю, роздільною здатністю та стійкістю до завад, а інтеграція цих розробок у сучасні навігаційні та далекомірні комплекси дозволить підвищити безпеку та загальну ефективність роботи систем навігації.

Ключові слова радіолокаційна система; радіотехнічна система; вимірювання; кореляція; обробка сигналу; аеронавігаційна система; радіоелектронна система.

Prokopenko I., Ilin O.**ANALYSIS OF THE OPERATION OF A CORRELATION RANGE METER AGAINST NON-GAUSSIAN INTERFERENCE WITH K-DISTRIBUTION**

This article analyzes the noise immunity of a correlation radio rangefinder that uses wide-band sounding signals with noise-like phase modulation against the background of non-Gaussian interference described by the K-distribution. The relevance of the work is due to the critical need for continuous and high-precision range data for navigation and control systems of manned aircraft and UAVs in harsh operating conditions, in particular under the influence of intense reflections from the underlying surface. In such situations, interference acquires a pronounced non-Gaussian character. One of the recognized models for describing complex scattering is the K-distribution. The paper presents a structural diagram of the radio rangefinder and describes the basic principles of its operation, including algorithms for forming a sounding signal, processing the reflected signal, measuring the delay time and radial velocity of the object. The corresponding mathematical formulas are given. The graph of the spectrum of the sounding signal and the cross-correlation function of the reference and reflected signals is presented. The structural diagram of the Doppler frequency shift compensation circuit and the principle of its operation are considered. Its functioning is critically necessary to eliminate the blurring of the correlation peak during target movement. The formula of the K-distribution SHR and its graphs for different values of its parameters are given. The main attention is paid to computer modeling of the system operation in the presence of noise with the K-distribution with different values of the shape parameter. The simulation results are presented in the form of the corresponding graphs of the cross-correlation function and the signal spectrum, which prove that correlation processing provides a clear separation of the maxima of the cross-correlation function even against the background of strong background noise. Accordingly, the use of noise-like signals in combination with correlation processing is a promising direction for creating the latest radio rangefinders with optimized accuracy, resolution, and resistance to interference, and the integration of these developments into modern navigation and rangefinder complexes will increase the safety and overall efficiency of navigation systems.

Keywords: radar system; radio engineering system; measurement; correlation; signal processing; aeronavigation system; radio-electronic system.

Received: 04.05.2026 p.

Accepted: 22.07.2026 p.

Published: 10.09.2026 p.