A New Detection Method Based on CFAR and DE for OFPS

Zezheng QIU[1], Tong ZHENG[2], Hongquan QU[2*], and Liping PANG[1]

[1]*School of Aeronautic Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing, 100191, China*

[2]*College of Electrical & Information Engineering, North China University of Technology, Beijing, 100144, China*

*Corresponding author: Hongquan QU E-mail: qhqphd@ncut.edu.cn

Abstract: Optical fiber pre-warning system (OFPS) is widely utilized in pipeline transport fields. The intrusions of OFPS need to be located. In this system, the original signals consist of noises, interferences, and intrusion signals. Here, noises are background and harmless interferences possessing with high power, and the intrusion signals are the main target of detection in this system. Hence, the study stresses on extracting the intrusion signals from the total ones. The proposed method can be divided into two parts, constant false alarm rate (CFAR) and dilation and erosion (DE). The former is applied to eliminate noises, and the latter is to remove interferences. According to some researches, the feature of noise background accords with the CFAR spatial detection. Furthermore, the detection results after CFAR can be presented as a binary image of time and space. Besides, interferences are relatively disconnected. Consequently, they can be eliminated by DE which is introduced from the image processing. To sum up, this novel method is based on CFAR and DE which can eliminate noises and interferences effectively. Moreover, it performs a brilliant detection performance. A series of tests were developed in Men Tou Gou of Beijing, China, and the reliability of proposed method can be verified by these tests.

Keywords: Optical fiber pre-warning system; constant false alarm rate; dilation and erosion

Citation: Zezheng QIU, Tong ZHENG, Hongquan QU, and Liping PANG, "A New Detection Method Based on CFAR and DE for OFPS," *Photonic Sensors*, 2016, 6(3): 261–267.

1. Introduction

Optical fiber pre-warning system (OFPS) is employed in monitoring the transport of petroleum and gas as well as forecasting the leakage to pipelines [1‒5]. Moreover, great losses have been avoided in the field of pipeline transport. Actually, the optical fibers are laid parallel with a pipeline in the same ditch. They are used not only to transmit data but also to extract vibration signals [6‒7]. In other words, intrusions on the ground are supposed to be forecasted by analyzing the extracted signals. Consequently, OFPS is of certain value to be studied [8‒9].

The vibration signals in OFPS consist of noises, interferences, and intrusion signals. Here, noises are background for OFPS. Interferences with high power enable may lead to fibers vibrate. However, the vibration does no harm to the fibers and pipelines. In other words, interferences are harmless. In addition, harmful signals from digging, hitting, and mechanical vibrations are harmful. In OFPS, a number of scholars have researched on the signal processing for OFPS. According to the previous

Received: 6 May 2016 / Revised: 7 June 2016

DOI: 10.1007/s13320-016-0342-8
Article type: Regular

study, signals can be extracted by refraction or reflection system [10−14]. Here, Zengguang Qin, from Ottawa University, Canada, closely studied the distribution of optical fiber vibration sensors which laid theoretical basis for the signal extraction in OFPS [14]. Meanwhile, most scholars are inclined to recognize harmful intrusions based on analyzing vibration signals directly. The team, from Tian Jin University, China, put forward a method to classify various vibration signals through support vector machine (SVM) [7]. However, with an increase in background complexity degree, interference cases are variable. Therefore, it is of great necessity to eliminate interferences and noises before recognition. Meantime, the detection accuracy can be improved by this proposal.

In this paper, we propose a new detection method to remove noises and interferences. From our early studies, we found that the vibration signals are non-stationary in the time dimension and its background distribution can be divided into two orthogonal Gaussian noises. At the same time, the envelope of synthesis signal obeys Rayleigh distribution. These features are identical to the requirements of constant false alarm rate (CFAR). Consequently, we are advised conducting the spatial detection by applying CFAR firstly. The traditional CFAR can be divided into three parts which are CA-CFAR [15], OS-CFAR [16], and A-CFAR [17]. In our system, the CA-CFAR is applied because it has an outstanding detection performance in the homogeneous background and relatively low computation cost. The corresponding threshold is derived by the given constant false alarm rate. Then the noised can be removed. Yet powerful interference exists on practical surrounding which is supposed to be detected by CFAR [18−20]. We can draw the conclusion that the interference needs further dispose. On the other hand, the result of detection can be presented as a binary image which means alarming and non-alarming, respectively. Therefore, dilation and erosion (DE), borrowed from image processing, is considered in OFPS. Here, dilation is used to bridge little disconnect cases within continuous alarm points. Meantime, erosion is applied to remove some discrete alarm points which are some false alarm points with high probability. In brief, interferences are supposed to be wiped off effectively.

In addition, we conducted practical tests for three typical time and space in Men Tou Gou district, Beijing. Various data were dealt by the new method which is provided in this paper. The results show that the detection method is very valid to improve the detection performance of harmful intrusions.

2 Detection method

2.1 Detection method outline

OFPS mainly comprises hardware and software modular. Its general structure is shown in Fig. 1. Its working principle can be listed as follows.

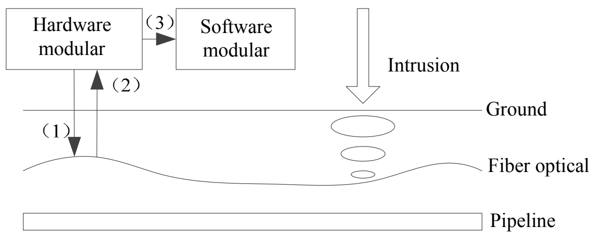

Fig. 1 General structure of OFPS.

(1) The light impulses are produced by the hardware modular and transmitted in the optical fibers;

(2) The changing refractive index of fiber, which is caused by elastic-optic effect, results in the change in light intensity. Finally, this kind of change returns to the hardware modular.

(3) The detection results of intrusions can be obtained by the signal processing and shown in the host computer.

The flow charts of the detection method which is presented in this paper are shown in Fig. 2. In detecting, noises eliminated by CFAR and interferences removed by DE are performed successively. After processing, the types of data vary distinctly. Firstly, the original data consist of noises, interferences, and intrusions. After the CFAR detection, massive noises are eliminated. Then, the interferences are removed by DE. In other words, data after detection only include intrusions.

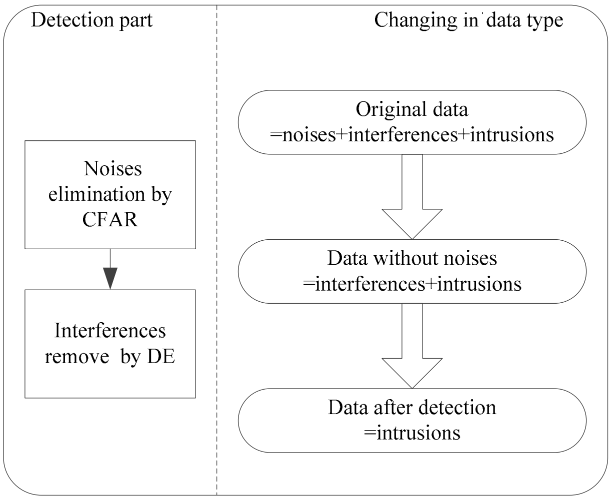

Fig. 2 Procedure of detection method.

2.2 Principle of provided method

The principle of CFAR and DE will be declared in this section. Meantime, we illustrate some workable rules in the view of OFPS.

2.2.1 CFAR

CFAR is a detection method which can derive threshold adaptively in accordance with the defined constant false alarm rate P_{f0}. The structure of CA-CFAR can be got by [15]. The test cell is surrounded by protection cells which are also surrounded by N reference cells. The reference cells are considered as the detection background. Firstly, the noise level can be obtained for different CFAR methods. Then, the threshold can be confirmed. Finally, the test cell is compared with corresponding threshold. If the test cell is great, the alternative hypothesis H_1 is fulfilled, giving an alarm to the test cell. Otherwise, null hypothesis, H_0, is achieved, and test cell is identified as noise. The derivations of specific formulas can be seen as follows.

The background of OFPS is Gaussian noise, of which the envelope follows Rayleigh distribution and its square obeys exponential distribution. Hence, its probability distribution function (PDF) is modeled as

$$f(x)=\frac{1}{2\mu}\exp\left(-\frac{x}{2\mu}\right),\ x>0 \tag{1}$$

where x denotes vibration signals. If vibration signals only consist of noises, then μ equals the variance of noises, σ^2. Otherwise, $\mu=\sigma^2(1+\text{SNR})$ and SNR are the signal-to-noise rate (SNR). Moreover, the false alarm probability is

$$\begin{aligned} P_f &= \int_0^{\infty} P\left(X>TZ\mid H_0\right) f_Z(z)dz \\ &= E_Z\left[P\left(X>TZ\mid H_0\right)\right] \end{aligned} \tag{2}$$

where T is multiplier of threshold, Z denotes noise level, $f_z(z)$ is PDF of Z, $E_z(\cdot)$ represents a mean of Z, and H_0 is null hypothesis.

Substitute (1) into (3), then

$$\begin{aligned} P_f &= E_Z\left[\int_{TZ}^{\infty} f\left(x\mid H_0\right)dx\right] \\ &= E_Z\left[\int_{TZ}^{\infty}\frac{1}{2\sigma^2}\exp\left(-\frac{x}{2\sigma^2}\right)dx\right] \\ &= E_Z\left[\exp\left(-\frac{TZ}{2\sigma^2}\right)\right]=M_Z\left(\frac{T}{2\sigma^2}\right) \end{aligned} \tag{3}$$

where $M_Z(\cdot)$ represents moment generating function (MGF) of Z.

Hence, the false alarm probability, P_f, is only decided by T when the distribution of Z is confirmed. T can be obtained by designing. P_{f0} is a designed false alarm probability before the detection.

CA-CFAR is typical of ML-CFAR, and we usually write Z as

$$Z=\sum_{i=1}^{N}x_i \tag{4}$$

where N is the data quantity of reference cell.

If the signals of reference cell are independent and identically distributed (IID), an excellent detection performance will be guaranteed. Moreover, exponential distribution is a special case of Gamma when α=1.

$$\begin{aligned} &p(v)=\frac{\beta^{-\alpha}v^{\alpha-1}}{\Gamma(\alpha)}\exp\left(-\frac{v}{\beta}\right) \\ &v\ge 0,\alpha\ge 0,\beta\ge 0 \end{aligned} \tag{5}$$

where $\Gamma(\cdot)$ is a Gamma function, and α and β are two parameters, $v\sim G(\alpha,\beta)$.

Furthermore, the accumulation of random variables obeying the same Gamma distribution also follows a Gamma distribution. Here, α needs to be accumulated.

Hence, Z obeys the following Gamma distribution:

$$Z \sim G\left(N, 2\sigma^2\right). \tag{6}$$

We can obtain $M_v(u)=(1+\beta u)^{-\alpha}$ with $v \sim G(\alpha, \beta)$. According to (3), the false alarm probability of CA-CFAR is

$$P_f = M_Z\left(\frac{T}{2\sigma^2}\right) = \left(1+2\sigma^2\frac{T}{2\sigma^2}\right)^{-N} = \left(1+T\right)^{-N}. \tag{7}$$

Hence, threshold multiplier can be identified as

$$T = P_{f0}^{-1/N} - 1. \tag{8}$$

In addition, the detection threshold S is

$$S = Z \cdot T. \tag{9}$$

Finally, the test cell is compared with the corresponding threshold S. If the test cell is great, it is thought as an alarm point. Otherwise, the test cell is identified as noise.

2.2.2 DE

(1) Dilation

Translating structural element A for X results in A_x. If the intersection of A_x and X is not null, give a tag for x. Assemble of X, which satisfies the above feature, is the so called dilation of X by A. We write it as

$$X \oplus A = \left\{x \mid A_X \cup x \neq \phi\right\}. \tag{10}$$

The method of dilation is comparing points in A with those in X one by one. If a point in A is in X, then the corresponding point in X is the image. Therefore, we apply it to bridge the gap of alarms in OFPS.

(2) Erosion

Translating structural element A of x results in A_x. If A_x is included in X, give a tag to x. Assemble of x, which satisfies the above-mentioned feature, is the so called erosion of X by A. We can express it as

$$X \Theta A = \left\{x \mid A_X \cap x \subset A_X\right\}. \tag{11}$$

The rule of erosion is doing the same steps like dilation. If the points in A are all included in X, then the points in X should be maintained. Otherwise, they do not belong to the erosion results of X by A. Hence, the disconnected points which have been dilated are finally eliminated by erosion in OFPS.

After vast simulation experiments, we found that $(1, 1, \cdots, 1)_{100\times1}$ and $(1, 1, \cdots, 1)_{1000\times1}$ can be considered as structural elements in DE of OFPS, respectively.

3. Experiment and analysis

The practical objections of OFPS are shown in Fig. 3, which are optical fibers, optical fiber fusion splicer, signal processing bar, and software display in Figs. 3(a)–(d), respectively.

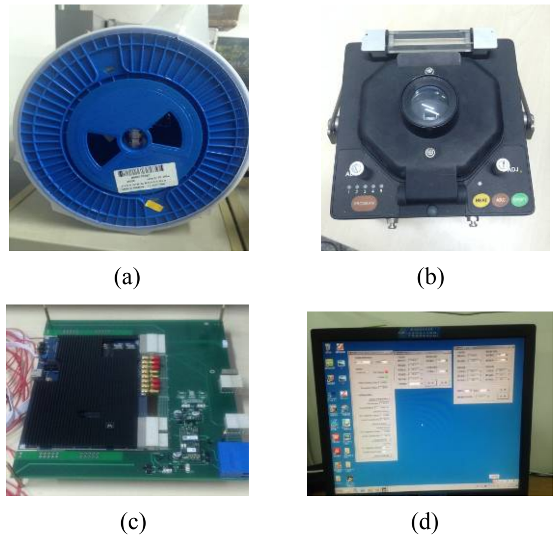

Fig. 3 Practical objections of OFPS: (a) optical fibers, (b) fusion splicer, (c) signal processing board, and (d) software display.

To verify the reliability and efficiency of algorithm proposed in this paper, we conducted practical tests in Men Tou Gou district of Beijing, China. Three kinds of intrusion results are listed in this paper, which are digging, hitting, and electric breaker. Three cases of experiment are shown in Table 1.

Table 1 Experiment background.

Cases	Vibration types	Situation (km)	Time (ms)
Case 1	Digging	41	1500–6000
		50	500–7500
		51	0–7500
Case 2	Hitting	47	0–7500
		48	0–7500
		58	0–7500
Case 3	Electric breaker	41	0–7500
		47	0–7500
		51	2000–6000

The cases of experiments are shown as follows:

• Case 1: The event of digging occurs at 41 km, 50 km, and 51 km. Their durations are 1500 ms–6000 ms, 500 ms–7500 ms, and 0 ms–7500 ms, respectively.

• Case 2: The event of hitting occurs at 47 km, 48 km, and 58 km. Their durations are all the same in 0 ms–7500 ms.

• Case 3: The event which is caused by electric breaker occurs at 41 km, 47 km, and 51 km. Their durations are 0 ms–7500 ms, 0 ms–7500 ms, and 2000 ms–6000 ms, respectively.

3.1 CFAR results

The consequences of processing the three sets of data by CA-CFAR are shown in Fig. 4.

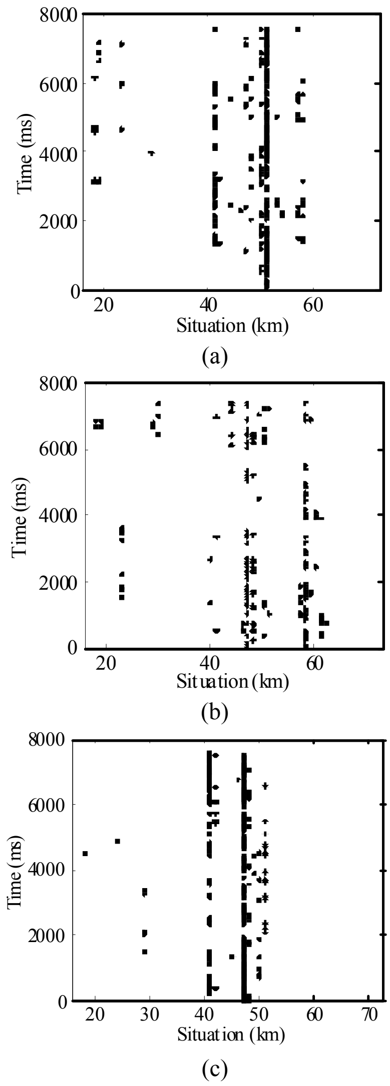

Fig. 4 Results of CFAR: (a) Case 1, (b) Case 2, and (c) Case 3.

According to the analysis of Fig. 4, the conclusions that we can obtain are listed as follows:

• Case 1: In Fig. 4(a), digging signals at 41 km, 50 km, and 51 km can be detected. Meanwhile, the vibration time is corresponded to the practical one. However, the interference at 16 km–28 km and 42 km–49 km can be detected through CFAR as well.

• Case 2: In Fig. 4(b), signals caused by hitting at 47 km, 48 km, and 58 km can be detected. And the vibration time is the same with the one in reality. Yet the interference at 18 km–41 km are also detected by CFAR.

• Case 3: In Fig. 4(c), signals of electric breaker at 47 km, 48 km, and 51 km are detected. Meantime, the vibration time is consistent with the actual time. But interference at 18 km, 24 km, and 29 km are detected by CFAR likewise.

According to above experiments, we can draw the conclusion that intrusion signals can be detected efficiently. However, interferences with high power are detected by CFAR. So they need to do further processing to eliminate interferences.

3.2 DE results

The data after CFAR are disposed by DE and the results are shown in Fig. 5.

Some conclusions can be obtained as follows:

• Case 1: In Fig. 5(a), digging at 41 km, 50 km, and 51 km can be detected. Meanwhile, the vibration time is corresponded to the practical one. Interferences detected by CFAR are eliminated effectively as well.

• Case 2: In Fig. 5(b), signals caused by hitting at 47 km, 48 km, and 58 km are detected. The vibration time is the same with the one in reality. Interferences detected by CFAR are also eliminated effective.

• Case 3: In Fig. 5(c), signals of electric breaker at 47 km, 48 km, and 51 km are detected. Meantime, the vibration time is consistent with the actual time. Interferences detected by CFAR are eliminated effectively likewise.

Through the processing of DE, we can find that interferences are supposed to be validly eliminated. Meanwhile, real intrusions are detected effectively.

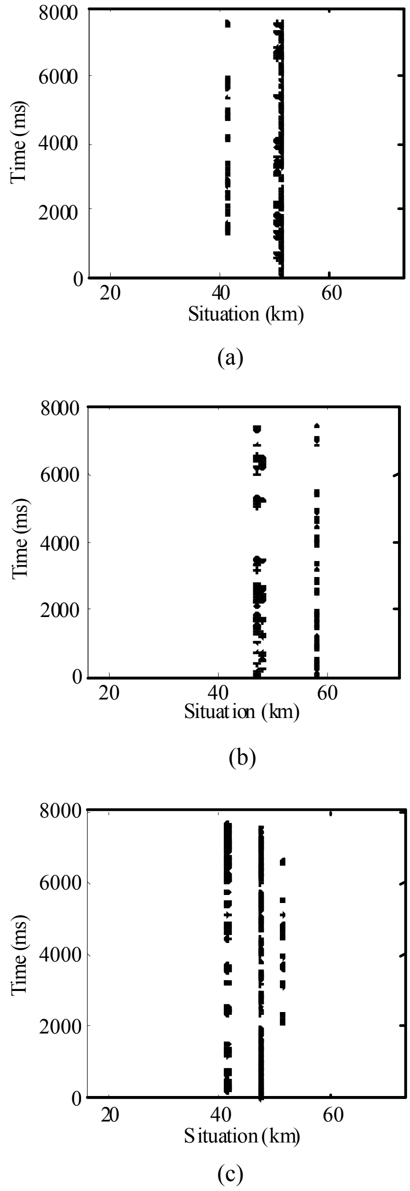

Fig. 5 Results of DE: (a) Case 1, (b) Case 2, and (c) Case 3.

4. Discussion and conclusions

According to the features of vibration signals, a brand-new method based on CFAR and DE is proposed in this paper to detect harmful intrusion signals. The method consists of two parts, noise elimination by CFAR and interference removal by DE. In the former part, CA-CFAR is adopted. It is the simplest one in a class of spatial CFARs and performs brilliantly in the homogeneous background. In addition, intrusion signals and interference of high power can be detected efficiently after the space-dimensional detection. Yet interference still exists after CFAR which cannot remove interferences. In the latter part, DE, which is introduced from the image processing, is adopted to do the further procession. From the results, the interferences are eliminated effectively. Field test data are used to verify the reliability of the proposed detection method. The measured data were collected in Men Tou Gou district of Beijing, China. After processing, the time and situations of intrusion signals can be located precisely and clearly. In other words, pre-warning function is achieved.

Acknowledgement

The authors are grateful to the anonymous reviewers for their critical and constructive review of the manuscript. This work was funded by the National Natural Science Foundation of China (No. 61571014).

References

[1] W. Liang, L. Lu, and L. Zhang, "Coupling relations and early-warning for 'equipment chain' in long-distance pipeline," *Mechanical Systems and Signal Processing*, 2013, 41(1): 335−347.

[2] J. Kang and Z. H Zou, "Time prediction model for pipeline leakage based on grey relational analysis," *Physics Procedia*, 2010, 25(2): 2019−2024.

[3] T. Zhang, Y. Tan, H. Yang, J. Zhao, and X. Zhang, "Locating gas pipeline leakage based on stimulus-response method," *Energy Procedia*, 2014, 61: 207−210.

[4] Q. Fu, H. J. Wang, and F. Qiu, "Pipeline leak detection based on fiber optic early-warning system," *Procedia Engineering*, 2010, 7: 88−93.

[5] Z. Qu, S. Jin, and Y. Zhou, "Study on the distributed optical fiber pipeline leakage pre-warning system and the method of signal analysis," in *Proceedings of the 6th International Pipeline Conference*, Calgary, Canada, pp. 677−681, 2006.

[6] W. Liang, L. Zhang, Q. Xu, and C. Yan, "Gas pipeline leakage detection based on acoustic technology," *Engineering Failure Analysis*, 2013, 31(6): 1−7.

[7] Z. Qu, H. Feng, Z. Zeng, J. Zhuge, and S. Jin, "A SVM-based pipeline leakage detection and pre-warning system," *Measurement*, 2010, 43(4): 513−519.

[8] Q. Lv, L. Li, H. Wang, Q. Li, and X. Zhong, "Influences of laser on fiber-optical distributed disturbance sensor based on Φ-OTDR," *Infrared and Laser Engineering*, 2014,12(43): 3919−3923.

[9] H. F. Martins, S. Martin-Lopez, P. Corredera, and M. L. Filograno, "Coherent noise reduction in high visibility phase-Sensitive optical time domain reflectometer for distributed sensing of ultrasonic waves," *Journal of Lightwave Technology*, 2013, 31(23): 3631−3637.

[10] Q. Li, C. Zhang, L. Li, and X. Zhong, "Localization mechanisms and location methods of the disturbance sensor based on phase-sensitive OTDR," *Optik-Interntional Journal for Light and Electron Optics*, 2014, 125(9): 2099−2103.

[11] Q. Lin, C. Zhang, and C. Li, "Fiber-optic distributed sensor based on phase- sensitive OTDR and wavelet packet transform for multiple disturbances location," *Optik-Interntional Journal for Light and Electron Optics*, 2014, 125(24): 7235−7238.

[12] A. R. Bahrampour and F. Maaoumi, "Resolution enhancement in long pulse OTDR for application in structural health monitoring," *Optical Fiber Technology*, 2010, 16(24): 240−249.

[13] L. Lu, Y. Song, X. Zhang, and F. Zhu, "Frequency division multiplexing OTDR with fast signal processing," *Optics and Laser Technology*, 2012, 44(7): 2206−2209.

[14] Z. Qin, "Distributed optical fiber vibration sensor based on Rayleigh backscattering," Ph.D. dissertation, University of Ottawa, Ottawa, 2013.

[15] H. Rohling, "Radar CFAR thresholding in clutter and multiple target situations," *IEEE Transactions on Aerospace and Electronic Systems*, 1983, AES-19(4): 608−621.

[16] M. E. Smith and P. K. Varshney, "Intelligent CFAR processor based on data variability," *IEEE Transactions on Aerospace and Electronic Systems*, 2000, 36(3): 837−847.

[17] S. Ward, M. Bélanger, D. Donovan, A. Horsman, and N. Carrier, "Automatic censored CFAR detection for nonhomogeneous environments," *IEEE Transactions on Aerospace and Electronic Systems*, 1992, 28(1): 286−304.

[18] R. Zhang, W. Sheng, and X Ma, "Improved switching CFAR detector for non-homogeneous environments," *Signal Processing*, 2013, 93(1): 35−48.

[19] G. V. Weinberg, "Management of interference in Pareto CFAR processes using adaptive test cell analysis," *Signal Processing*, 2014, 104: 264−273.

[20] B. Shi, C. Hao, C. Hou, X. Ma, and C Peng, "Parametric Rao test for multichannel adaptive detection of range-spread target in partially homogeneous environments," *Signal Processing* 2015, 108: 421−429.