Determination of aircraft current location on the basis of its acoustic noise

Abstract — **In this paper the algorithm of signal detection by means passive acoustics and digital data processing is proposed. This algorithm is original and contains the processing of signals, which are received by several acoustic aerials. For signal detection the calculation of wide-band ambiguity function together with its projection on time axis are used. All the calculations are executed with the real signals. As the result the location of the aircraft on Cartesian coordinate plane is observed. The suggested algorithm is also proposed to use for measuring of aircraft noise with the aim of environmental protection.**

Keywords — acoustic noise; ambiguity function; correlation function; low-pass filter; passive radar; resampling; sampling.

I. INTRODUCTION

The development of science caused the construction of numerous methods of objects research. Each of these methods can provide a wide spectrum of various information about it. But the special place is occupied by the location of different types: GPS-location, radio location, visual observation and many others, depending on the necessary information, research conditions and so on.

This work is dedicated to special method of determination of object (aircraft) location, relying on its noise. This method is called passive acoustic location. There are active location and passive location.

In active location there are two operational elements: transmitter and receiver, located in a one place (radar). The transmitter sends the signal to the object. This signal is reflected or retransmitted back to the radar. Passive acoustic location, which is used in this work, means that there is a receiver, which records the noise, emitted by all the objects around.

The authors try to explain, that with the help of special signal processing it is possible to measure speed, coordinates and other parameters of the noise source. The coordinate's determination can be used in location. The measurements of the noise level can be useful for ecologists for environmental protection, or provide basic information about the nature of the noise source. The information about aircraft speed can be used for different purposes. Thus, this method is very useful in solution of actual problems in different spheres of our life. However this particular work considers only aircraft location, that is, the computation of an array of aircraft coordinates.

II. RELATED WORKS

The investigation of passive location by numerous scientists all around the world ones more proves the importance of this sphere. All these investigations are performed for various purposes and are directed to search of the best method, the best algorithm, which will satisfy the most requirements of the consumer and at the same time to find the method, which will be unique for some sphere of technical activity.

Manish Kushwaha in his work [1] tried to localize sensor node in some network with the help of mobile acoustic beacons. The idea was that a sensor network deployment scenario with many favorable characteristics in numerous application areas was the dispersal of sensor nodes from a low-flying unmanned aerial vehicle platform. After deployment, an acoustic beacon mounted on the aircraft could send a radio message followed by an acoustic signal at random intervals. All the nearby sensor nodes could estimate their distance from the beacon by measuring the time-of-flight of the sound. In order to calculate the range from the time-of-flight of the acoustic signal, the departure and arrival times of the signal were identified and measured. The beginning of the transmission was measured at the beacon, while the time of arrival was measured at the receiving sensors. The range calculation was performed on the receivers, thus the beacon sent the starting time to the receivers in a radio message. Formally, a generalized self-localization problem was defined as follows. Given node IDs and their ranges from each other conjectured the relative physical location of each node in the network. A few anchor nodes could be provided to transform relative positions to absolute locations.

The main contributions was the acoustic ranging method providing increased range and accuracy, the localization algorithm based on the novel idea of a mobile acoustic beacon and the ability to handle multipath effects.

Manish Kushwaha's another work [2] is dedicated to another model. There was considered a wireless sensor network of acoustic sensors in a planar field and far-field stationary acoustic sources coplanar with the sensor network. The goal of that work was to estimate the 2D position of all the sources. The idea was to separate the sources in frequency domain using the received power spectral density (PSD) from the sensors, and then use the separated sources for localization. Author proposed a maximum likelihood (ML) estimation method for source separation and Bayesian estimation for localization.

Mikhniuk A. [3] tried to localize the noise source with the help of algorithms of signal processing, matched with sea waveguide. The noise emitter was located under water in some depth. The non-directional receiver was floating on the water surface. Different rays connected the points of emitting and reception. Knowing the profiles of sound velocity, it is possible to determine the coordinates of noise source using the measured parameters of these rays. The received signal was considered as the sum of amplitudes of the signals, which arrived to each beam. The correlation function of this signal and standard signal were calculated, and finishing the algorithm with the maximum likelihood ratio the coordinates of the noise source were obtained through the maximum of correlation function.

The work of Bert Van Den Broeck [4] was dedicated to sound source localization for small microphone arrays using time-domain cross correlation function. The model was the following. Each microphone array was mounted on a device (further referred to as an acoustic node) with a local DSP processor and with wireless networking capabilities. Together, these acoustic nodes form a so-called wireless acoustic sensor network, where the nodes can work together to perform a certain task such as speech enhancement. Sound source localizer algorithms can generally be split up in 3 major groups, based on:

a) Time delay of arrival estimation mostly by means of cross correlation;

b) Steering out beams and finding high energy sound sources, often called steered power response;

c) Eigenvalue based algorithms such as multiple signal classification.

When only small microphone arrays are considered, the delays are small, and then a cross correlation can be done more efficiently in the time-domain. However, then the original frequency-domain-based PHAT (phase transform) weighing scheme cannot be used. Therefore that paper has introduced a low complexity time-domain phase transform alternative based on an adaptive linear prediction whitening filter.

Lvov A. [5] proposed a method of contactless determination of sound source coordinates by the means of acoustic location. Prior data: the dimensions of the object were much less, than the area of its possible location and the object was a noise source, which can be detected by microphones. The localization was executed by the means of passive acoustic location. The microphones were located on the fixed points with the known coordinates, and the emitting sound can be detected at least by some part of these microphones. Due to object's motion the signal arrives to microphones with different time delays and amplitudes. If for the pair of microphones with known coordinates the difference of signal arrival to them is known, then it can be supposed that the object lies on the surface of hyperboloid with these microphones in its focus. If to use three microphones then the object is located on the intersection of two hyperboloids – on ellipsoid. Four microphones provide a two-points or even single-point location of the object. Five microphone gives the possibility to determine the object definitely. All the calculations were done by microcontrollers.

III. STATE OF THE ART IN AIRCRAFT NOISE MONITORING

For aircraft noise management, systems of "budget" are used at some major airports in Europe; some of them use indices, calculated with actual noise measurements. Since these systems provide the community with information on the evolution of noise impact, they are requested to rely upon exhaustive databases.

Environmental Noise Monitoring System is used for routine noise measurements from aircraft, road traffic, construction sites, rail yard and rail pass-by noise, factories. In the system a main unit is an Environmental Noise Monitor (Fig. 1) with Sound Level Meter, Outdoor Microphone Set, Environmental Noise Processing Program, Noise Identification Unit (to detect a direction from sound source).

Main system service is a Data Processing of Environmental noise data by usage of processing software. The 4D trajectory (i.e. *x*,*y*,*z* as a function of time) of an aircraft is crucial information for an airport environmental management system.

Figure 1. Noise monitoring terminal with 4 microphones system on a site [1]

Integrated aircraft noise monitoring systems, as adopted by major airports, are based on cross-referencing of noise and aircraft fight paths information. Sound levels are measured in remote noise monitoring stations located outside the airport (Fig. 1).

Usually each flight path is recorded real-time by the secondary radar, receiving flight information from the beacon. Aircraft noise events are identified by sound level threshold overstepping detection mainly, but the pending problem is still to warrant what is actually an aircraft noise event.

The ability to identify aircraft without access to the airport's radar system may be a valuable feature for local authorities or other organizations that have a requirement to evaluate aircraft noise when they have had to approach the airport for tracking information in order to be certain of the identification of specific noise events [6].

One of the solutions uses aircraft noise that is distinguished from other sources of noise by a 4 microphone system, which identifies the location and direction of travel (in three dimensions) for each noise event (Fig. 1). When the same noise does not reach to two microphones at the same time, there is elevation angle from sound source to microphones. Two microphones on vertical line gives us an angle to noise source and in further step a climbing angle is calculated from the time difference. Four microphones may provide us noise direction in three dimensions.

The secondary surveillance radar (SSR) Radar Receiver may assist in distinguishing Aircraft Noise Events form other intermittent noise events. For example, the NA-37 (Rion's 6th generation Aircraft Noise Monitor) offers such unique features including the ability to identify aircraft noise events without access to airports' radar/track monitoring systems.

The system can also optionally include an SSR Radar Receiver enabling aircraft to be identified from their unique SSR Radar Identification Code. Combination of identification result by acoustic method and identification result by RF method should result in integration of the both identifications and final identification result.

At small airports, especially those with mainly General Aviation traffic, operations are usually under Visual Flight Rules and no radar is available for air navigation. The aircraft types operating at these airports are usually not equipped with an ADS-B or even mode-S transponder. Even at medium-sized airports radar data is not always available and in the case it is, it appears usually very costly to obtain it from the Air Navigation Service Provider.

In real life human hearing easily identifies aircraft noise. Whereas the aircraft localization system can provide the aircraft position in 4D, it is not capable of determining the aircraft identity. To this end a specific aircraft identification system should be developed and used. Replacing the brain by a computer that is blind, it is necessary to find out from the audio signal some descriptors or cues that may guarantee that it is an aircraft noise [7].

The key point is that it is necessary to use the spectrum of the noise because the time dependency of global noise intensity cannot be considered as specific of aircraft noise. Traditional recognition systems are based upon a fix number of characteristics (descriptors) of the noise signal, whatever the source that should be identified. Such methods perform well in the area of vocal recognition (there is a dictionary of words), but is inappropriate for environment noises which are more complex and non-stationary.

In the pattern recognition technology simplistically presented here, recognition of aircraft as a source of a noise event is realized from a limited number of characteristics corresponding to the source (aircraft) that has to be recognized. Moreover, the knowledge may be built from a relatively low number of examples provided during the "learning stage". Indeed, the system described in the paper is motivated by a selection of relevant and non-redundant airplane noise characteristics [8].

This approach has been proven in both theory and practice. It is effective in enhancing learning efficiency, increasing predictive accuracy and reducing of complexity of required learning results [9, 10, 11].

IV. ALGORITHM DESCRIPTION

The algorithm can be divided on some parts, steps, which are considered as follows.

1. Record of the noise. The record is executed with the help of several acoustic antennas with four microphones in each one. Any number of antennas can be used, but for plane target localization three them is enough. The antennas must be located near

each other or can be separated in any way, but not on the straight line. The distance of satisfactory record depends on the microphone sensitivity, the amplitude of the useful noise relatively other noises. Also it depends on the environment character (like relief type).

2. The Wideband Ambiguity function is used for signal detection emitted by the target with unknown velocity [12 - 14].

The cross-ambiguity function for two random processes $X(t)$ and $Y(t)$ can be defined as an average

$$\chi(\tau,\alpha) = \sqrt{|\alpha|}E\left\{(X(t)) - m_x)(Y^*(\alpha(t-\tau)) - m_y)\right\},$$

where $\alpha = (c-v)/(c+v)$ is a scale coefficient, c is the velocity of the wave, v is the target velocity, $Y^*(t)$ is a complex conjugate of the random process $Y(t)$, m_x and m_y are mathematical expectations of $X(t)$ and $Y(t)$.

For the ergodic random signals we can consider that the cross-ambiguity function is [15 - 17].

$$\chi(\tau,\alpha) = \lim_{T\to\infty} \frac{\sqrt{|\alpha|}}{T} \int_{-T/2}^{T/2} x(t) y^*(\alpha(t-\tau))dt$$

where $\alpha = \dfrac{c-v}{c+v}$ is a scale coefficient,

v is a radial target velocity.

For the passive radar with *m* receivers we can represent the wideband ambiguity function in the form for continuous signals

$$\chi(\tau,\alpha) = \sum_{k=1}^{m}\sum_{j=1}^{m} \frac{\sqrt{|\alpha_k|}}{t_2 - t_1} \int_{t_1}^{t_2} (x_j(t)) - m_{x_j})(x_k^*(\alpha_k(t-\tau_k)) - m_{x_k})dt,$$

and in the form of

$$\chi(\tau,\alpha) = \frac{1}{N}\sum_{k=1}^{m}\sqrt{|\alpha_k|}\sum_{j=1}^{m}\sum_{i=1}^{N}(x_{ij} - m_{x_{ij}})(x^*_{\alpha_k\ i-\tau_k k} - m_{\alpha_k\ i-\tau_k k})$$

for discrete signals. In these expressions *m* is the number of receivers, *n* and *k* are receiver numbers, *N* is the quantity of time samples, *i* is a sample number.

In order to obtain the method of coordinate measurements, which is free from the any velocity of the flying target, we must find velocity of the target v and corresponding to it scale factor α for which the ambiguity function $\chi(\tau,\alpha)$ has a maximum value for the given value of the difference of arrival τ

$$\alpha_{\max} = \underset{\alpha}{\mathbf{Argmax}}\left\{\chi(\tau,\alpha)\right\}.$$

The signal realizations with different scale factors α can be obtained by the resampling of the signal x.

That is why we must calculate correlation function of two random processes $X(t)$ and $Y(\alpha_{\max}t)$, which is a cross-section of the ambiguity function (Fig. 2), which provides the maximum value of the ambiguity function $\chi(\tau,\alpha)$.

3. Correlation function. So, the noise is digitally recorded. To make some operations with sound it is necessary to discretize (sample) it for digital processing. The obtained signal consists of large number of noises, emitted not only by the aircraft, but also by other objects around antennas.

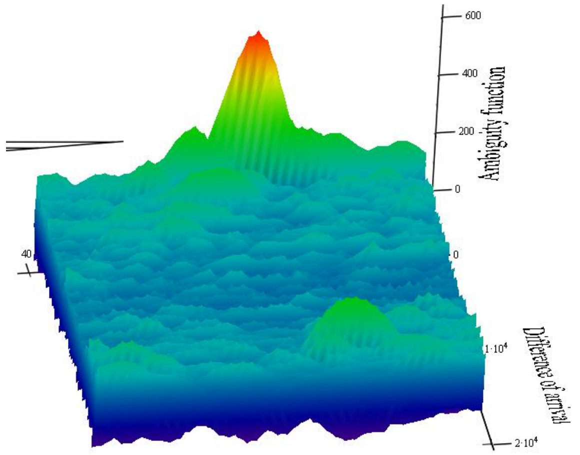

Figure. 2. Ambiguity function. Dependence of the ambiguity function from the difference of arival (in conditional units) and velocity (in conditional units)

The useful signal must be separated from noises. For this purpose the antennas are considered in pairs. The correlation function helps to detect the signal of aircraft in the mixture of noises. It is calculated according to Wiener–Khinchin theorem, which claims, that correlation function can be calculated by inverse Fourier transform (IFT) of the product of spectrum of the first signal and complex conjugated spectrum of the second signal and for obtaining more sharp form of curve the spectral density is normalized (phase correlation) [18]

$$R_{xy}(\tau) = \int_{-\infty}^{\infty} \frac{S_{xy}(f)}{\left|S_{xy}(f)\right|} e^{j2\pi f\varepsilon} df \ ,$$

where S_{xy} is mutual spectral density of two given signals, which is equal to the a product the spectral density of the first signal and complex conjugated spectral density of the second signal.

Instead of discrete Fourier transform (DFT) the fast Fourier transform (FFT) was used for greater performance. For determination of aircraft coordinates it is enough to use only three antennas. The locus for the processed correlation functions on the coordinate plane has the form of hyperboloid. The object can be located on this hyperboloid. The correct position of aircraft is on the intersection of hyperboloids, formed by the pairs of antennas.

4. Filtration. In ideal case the maximum of correlation function is well seen. But in real case the picture can look not so clear. Even the case when it is not seen at all is possible. Thus, the application of different filtration methods is required.

5. Projection. Finally, the “cleared” picture must be projected on the coordinate plane, which must be designed, that is, the origin of coordinates and the coordinates of antennas must be determined. Then, relying on these data the coordinates of the aircraft are determined. To observe the motion of aircraft, it is necessary to calculate the its coordinates for different samples of the signal with some constant step.

V. EXPERIMENT DESCRIPTION

An experimental setup consists of four acoustic antennas (named M51, M52, M53 and M54) that are located near the runway. The coordinate plane consists of all these antennas and a 1000-meter part of runway (Fig. 3).

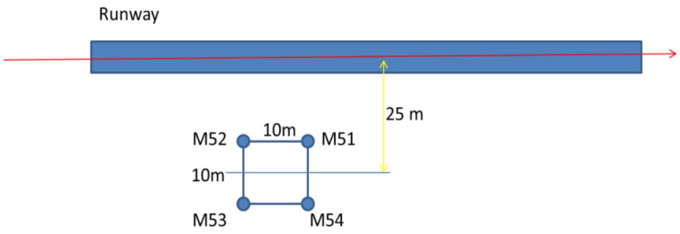

Figure. 3. The scheme of experimental installation

The origin of coordinates is located in the beginning of the runway part (from the left in the figure). The X-axis is located along the middle of the runway, Y-axis is directed to the antenna side, Z-axis responds for height. The presence of fourth antenna is explained as following – sometimes the ambiguity function can have more, then one maximums, or the maximum is not well defined. The fourth antennas provides additional accuracy of measurements. The coordinates of antennas are: M51(505;20;0), M52(495;20;0), M53(495;30;0), M54(505;30;0). These data will be used for projection of ambiguity function on this plane.

Let's at first consider two antennas: M51 and M52. The recorded noise is introduced into computational software (MathCAD 15). The calculation of correlation function of the whole signals is not acceptable, because of the necessity of aircraft coordinates calculation in several points. For this purpose each signal is divided into equal parts called frames. The more frames – the more positions of the object can be calculated. As the signal is discrete, its spectrum is periodical. Often the one period of the spectrum can intersect another one, distorting the final picture. This problem is solved by a simple manipulation – addition of zero samples into the frame. This operation moves the spectrum periods one from another.

To obtain the ambiguity function for the objects with different velocities it was calculated for some set of sampling frequencies, i.e. the set of interpolation procedures was executed. Standard procedure of interpolation is:

- insert of zero samples on the place of those, which have to be calculated;

- application of digital low-pass filter to exclude the spectrum components, which are unnecessary.

But there is also the procedure of interpolation with the help of DFT (FFT):

- calculate DFT (FFT);

- insert the necessary zero samples into the middle of the spectrum (in our case the number of zeros is equal to the number of spectral samples, as it is necessary to double the frequency);

- calculate inverse DFT (FFT).

The low-pass filter procedure is simple. It is necessary to calculate some threshold of spectrum amplitude. Then equate the samples, that don't satisfy the threshold, to zero. As we have two signals and they are shifted respectively each other (there is some distance between the antennas and the sound arrives to them in different time moments). The 2-dimensional (2D) dependence of response of matched filter on the signal, shifted by time respectively the given signal, matched with this filter is called ambiguity function. The matched filter is built by calculation of correlation function. The set of samples of ambiguity function from velocity domain (Fig. 2), which have the maximal response of the filter is selected. The resulting set is the time-domain ambiguity function.

Now, it is necessary to project this function on the coordinate system. At first let's choose the boundaries of the coordinate system and calculate the difference of signals arrival from each point of this space to antennas under consideration, taking into account the preliminary data about the coordinates of antennas. After the calculation of signals arrival difference (Fig. 4) it is possible to substitute the value of ambiguity function into each point of this space.

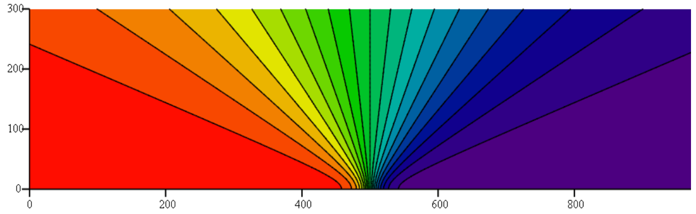

Figure. 4. The distribution of signals arrival difference from two orthogonal range coordinates (in meters)

In Fig. 4 it is shown the distribution of signals arrival difference to antennas M51 and M52 in 2D space (X- and Z-axes) along the middle of runway part with length 1 kilometer and till the height 300 meters.

Repeating the same for another pair of microphones we obtain two ambiguity functions, projected on the coordinate system. The object lies on the intersection of these functions (Fig. 5).

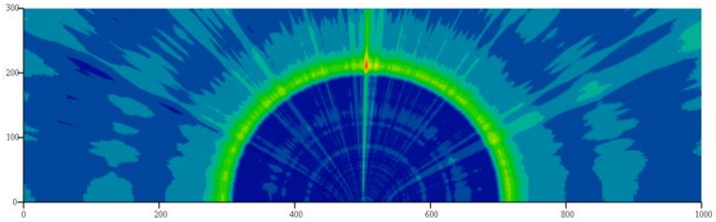

Figure. 5. Object location on the intersection of ambiguity functions

Performing the calculations for another pair of coordinates it is possible to define the location of the object in another coordinate plane. If the result is not sufficient the fourth aerial is took into consideration.

VI. CONCLUSION

Passive acoustic location connects the notion of the noise and the information, brought by it. This information includes the coordinates of the source. With the help of spectral analysis and filtering it is possible to detect the location of the object in plane near the radar in separate time moments.

Use of the ambiguity function instead of a correlation function gives us the possibility to obtain signal processing algorithm free of the possible velocity of the aircraft. This gives us the possibility of using antennas with a big base (distance between microphones) with a high distance resolution.

This method has advantages and disadvantages among the other methods. The low cost of installation makes passive location accessible to users. The simplicity of coordinate determination algorithm gives the possibility to change the parameters anyhow and to adapt it for various situations.

Another problem – location of the objects with radio absorbing cover. Passive acoustic location solves this problem. It is difficult to hide the sound of engine, screw crew, and other noisy operational elements, and acoustic location detects them in any depth, daytime and season, regardless on the weather. This method is really used today with this purpose. Moreover, passive acoustic location can provide not only by the coordinates of the object, but also define the speed, noise level of the source and so on. It may help the scientists of other scientific spheres.

Unfortunately, the calculation of correlation function and ambiguity function takes a lot of time, but contemporary equipment must operate in on-line regime. This problem can be solved by using fast calculation algorithms such as Fast Fourier Transform. Also, the low detection distance makes passive location uncompetitive with other detection methods, like GPS and radio location. The probability of object detection rapidly falls with the decrease of useful noise level relatively other noises.

Some of disadvantages can be reduced or removed, for example, by decrease of sampling frequency, optimization of calculations, application of high-sensitive microphones and so on. Some advantages can be improved. All these modifications can form a competitive, alternative method of object location and solution of various actual problems.

REFERENCES

[1] Manish Kushwaha, Karoly Molnar, Janos Sallai, Peter Volgyesi, Miklos Maroti, Akos Ledeczi "Sensor Node Localization Using Mobile Acoustic Beacons". Institute for Software Integrated Systems, Vanderbilt University, IEEE MASS, 2005.

[2] Manish Kushwaha, Xenofon Koutsoukos, Peter Volgyesi and Akos Ledeczi "Acoustic Source Localization and Discrimination in Urban Environments". Institute for Software Integrated Systems (ISIS), Department of Electrical Engineering and Computer Science, Vanderbilt University, Nashville, 2009.

[3] Михнюк А. Н. Определение координат источника звука с помощью согласованных с морским волноводом алгоритмов обработки сигналов // Научный центр волновых исследований Института общей физики им. А. М.Прохорова / Акустический журнал. - М: НЦВИ, 2009, том 55, №3, с. 401 – 406.

[4] Bert Van Den Broeck[1,3], Alexander Bertrand[1,2], Peter Karsmakers[1,3], Bart Vanrumste[1,2,3], Hugo Van hamme[1], Marc Moonen[1,2] "Time-domain generalized cross correlation phase transform sound source localization for small microphone arrays", [1]ESAT, KU Leuven, [2]IBBT, Future Healt Department, [3]MOBILAB, KH Kempen, Kleinhoefstraat 4, 2440, Geel, Belgium, Proceedings of the 5th European DSP Education and Research Conference, 2012.

[5] Львов А. В. Распределенная микроконтроллерная система акустической локации / А. В. Львов[1], М. Н. Агапов[2], А. И. Тищенко[3] // [1]энергетический факультет АГТУ имени И.И.Ползунова, кафедра электротехники, [2]факультет информационных технологий АГТУ имени И.И.Ползунова, кафедра САПР, [3]энергетический факультет АГТУ имени Ползунова,

кафедра общей электротехники / Журнал радиоэлектроники №11. – Барнаул: 2010.

[6] Richard J. Peppin, “A Way to Measure Aircraft Noise, to Discriminate Among Ground and Air Sources, and to Identify Wind Generated Noise”, (www.ScantekInc.com).

[7] S. McAdams, "Recognition of sound sources and events", Thinking in Sound: The Cognitive Psychology of Human Audition, Edited by: McAdams, S., Bigand, E., Oxford: Oxford University Press, 1993, pp. 146-198.

[8] B. Barbo, C. Rosin, J.-M. Machet, “A pattern recognition approach for aircraft noise detection”, Inter-Noise-2009, 23-26 of August 2009, Paper in 09_383., p. 9.

[9] D. Koller and M. Sahami, “Toward optimal feature selection”, Proceedings of the Thirteenth International Conference on Machine Learning, 1996, pp. 284–292.

[10] A. L. Blum and R. L. Rivest, “Training a 3-node neural networks is NP-complete”, Neural Networks, 5, 1992, pp.117 – 127.

[11] H. Almuallim and T. G. Dietterich, “Learning boolean concepts in the presence of many irrelevant features”, Artificial Intelligence, 69(1-2), 1994, pp. 279–305.

[12] R.B. Sinitsyn, F.J. Yanovsky; "Kernel estimates of the characteristic function for radar signal detection", Proc. of European Radar Conference, 2005, pp. 53-56.

[13] R.B. Sinitsyn, F.J. Yanovsky; "Nonparametric signal processing in noise radar”, Aplied Radioelectronics, 12, № 1", 2013, pp. 72-78.

[14] Anna Ya Tarkovska; Rustem B Sinitsyn, "Ambiguity function of passive acoustic radar", Signal Processing Symposium (SPS), 2013, pp.1-4.

[15] R.B. Sinitsyn and F.J. Yanovsky, Acoustic Noise Atmospheric Radar with Nonparametric Copula Based Signal Processing, “Telecommunications and Radio Engineering”, 2012, Vol. 71, No. 4, pp. 327-335.

[16] Rustem B. Sinitsyn, Felix J. Yanovsky, MIMO Radar Copula Ambiguity Function, Proceedings of the 9th European Radar Conference, 2012, Amsterdam, The Netherlands, pp. 146-149.

[17] R.B. Sinitsyn and F.J. Yanovsky, Copula Ambiguity Function for Wideband Random Radar Signals, The International IEEE Conference on Microwaves, Communications Antennas and Electronic Systems, Tel-Aviv, Israel, November 7-9, 2011, 5 pp.

[18] W.A Hoge, "A subspace identification extension to the phase correlation method [MRI application]." Medical Imaging, IEEE Transactions on 22.2, 2003, pp. 277-280.