Radar for Rescuers and Methods for Target Identification

Oleg Sytnik

A.I. Kalmykov's Center of Radiophysical Sounding of the Earth,
National Academy of Sciences and National Cosmic Agency of Ukraine 12, Acad Proskura St.,Kharkov, 61085, Ukraine
ssvp127@gmail.com

***Abstract*-The method of detection and identification of a low Doppler target under conditions of intensive disturbances having fluctuating character is investigated in this article. The proposed algorithm for calculating the estimations of the target spatial position and the Doppler frequency translation of a signal reflected from the target is an optimum from the standpoint of the maximum of likelihood. The algorithm was based on the principle of the combined processing of signals from spaced sensors in order to obtain the optimum estimations of signal parameters. The analysis is carried out both in the spectral and in the time domains which makes it possible to extract a maximum amount of information about the object under investigation with disturbances of different character and level. The results of the algorithm modelling are presented; the characteristic features of its performance in actual practice are discussed.**

Keywords*- *Targets Selection; Orthogonal Decomposition; Algorithm; Reflected Signal; Aantenna; Doppler's Frequency Shift

I. INTRODUCTION

When using a method of radio sounding of objects hidden by barriers being opaque to a visual observation, the problem of target identification against the background of reflections from surrounding objects and estimation of its parameters arises [1-5, 10-14]. Every target is characterized by two parameters of the reflected signal, the value of delay determining the distance between the locator antenna and the target and the Doppler frequency shift of a carrier oscillation due to the movement of the object or its parts. If the object moves quickly enough, i.e. the Doppler frequency shift of a carrier oscillation is about 0.1-1 kHz, the problem of the target identification may be solved by the Doppler selection method [2]. But a unique identification of targets becomes problematic when the spectral oscillation density caused by the object movement is near zero frequencies, where a considerable level of low-frequency equipment noises is observed and the intensity of the desired signal is determined by the position of the object relative to the antenna. One of the solutions of this problem is the application of multiposition coherent systems in which the procedure of the target detection and identification is based on calculating cross-correlative functions between the observed realization of the reflected signal and the reference signal [3]. The radiated signal is used as a reference signal. When the object or its separate parts move relatively to the antenna system, a signal delay variable in time can be observed:

$$\tau(t) \approx \tau_0 + \Delta\tau(t), \tag{1}$$

where τ_0 is the initial delay, $\Delta\tau(t) = \Delta r(t)/c$ is the increment of the signal delay, $\Delta r(t)$ is the increment of the distance from the target to the locator, c is the speed of the signal propagation.

In a stationary case when the object is fixed in position to obtain optimum delay estimations from the viewpoint of the maximum likelihood (1) it is necessary to develop an algorithm of the signal processing of a locator with the estimation accumulation in time [4]. If the object or its separate parts move, the accumulation time is limited by a value of a correlation interval of information process and, consequently, the dispersion of obtained estimations increases. This restricts a realization possibility of such algorithms for a number of important practical problems. The use of algorithms of the dynamic Kalman filtering [6] to obtain optimum estimation sequences is not always acceptable too, because a steady operation of an algorithm and the reliability degree of parameter estimations of information process depend on the adequacy of the model which is included in the algorithm as a priori. For example, if the object moves relatively to sensors, and separate parts of the object are in its chaotic motion relative to its center of gravity which, in turn, is an information process necessary to identify the object, then it will be difficult to build an analytic model of the object movement to realize the Kalman methods. Besides, the higher is the model precision, the larger is the bulk of calculations falling on each count of the observed process which can become an insuperable technical difficulty for handheld radars used for the problems of short-distance detection. The article offers the approach to the synthesis of statically optimal algorithms of parameter estimation of signal reflected from mobile targets, this approach being based on the piecewise-linear approximation of the plane "the Doppler frequency shift-delay". The combined estimation of the Doppler frequency shift and delay which is the optimum from the viewpoint of the maximum likelihood is calculated in the corresponding time-and-frequency channel. Then this estimation is compared with the corresponding estimations of adjacent channels. This information is used to determine the law of the object movement. The two-position receiving system is accepted as a basis.

II. PROBLEM STATEMENT

Let us consider a spaced receiving system consisting of two identical antenna elements. The signal reflected from the target comes to the receiving system blended with a normal Gaussian noise with dispersion σ_0^2 and a zero mean:

$$r_1(t) = s(t) + n_1(t), \tag{2}$$

$$r_2(t) = s\big(t - \Delta\tau(t)\big) + n_2(t), \tag{3}$$

where $\Delta\tau(t)$ is the signal delay variable in time which is caused by the object movement with respect to the receiving elements; $s(t)$ is the desired signal reflected from the target and phase-modulated by a pseudorandom sequence (the Mersen code) [6]; $n_1(t)$, $n_2(t)$ are the fluctuating processes which are uncorrelated with each other and with the desired signal and which have zero means and dispersions σ_0^2 in corresponding receiving elements.

Let us divide time interval $[-T/2, T/2]$ in which the realizations of processes (2), (3) are observed into m time intervals within which the dependence $\Delta\tau(t)$ can be assumed as linear. This assumption, in turn, predetermines a constancy of the Doppler translation within the limits of an elementary interval. In other words, the following relationship is true in this case:

$$\Delta\tau(t) = \Delta\tau_n + \Delta\dot{\tau}_n (t - t_n), \tag{4}$$

where $t_{n-1} \le t \le t_n$, $t_n = nT/m$, $n = 1, 2, ..., m$; $\Delta\tau$ is the increment of the relative signal delay in the n-th time interval; $\Delta\dot{\tau}_n$ is the delay change speed in the elementary observation interval.

In a general case, the vector of information parameters $\vec{X}_n$ observed within the interval of the process realization is not only the delay Function (4), but it is also the function of a big number of unknown parameters:

$$\vec{X}_n = \left(\Delta\tau_n, \Delta\dot{\tau}_n, \vec{z}^T\right)^T, \tag{5}$$

where $\vec{z}^T$ is the vector of unknown parameters, for example, it is the inexactly known central frequency of the signal spectrum, amplitude factor etc.; the upper symbol T denotes the transposition operation.

Thus, it is necessary to obtain the totality of the estimations $\left\{\hat{\vec{X}}_n\right\}$ of vector $\left\{\vec{X}_n\right\}$ which are the optimum from the viewpoint of the maximum likelihood if the piecewise-linear approximation of the Doppler frequency shift between the adjacent observation intervals is assumed to use them subsequently to derive the rule of the target identification over the whole observation interval.

III. DERIVATION OF BASIC RELATIONSHIPS

The sequence of the observed process realizations at the antenna outputs of the receiving system is presented as a set of the Gaussian vectors $\vec{R}_n(\vec{X}_n)$ with a zero mean. The multivariate density of probability of the vector $\vec{R}_n(\vec{X}_n)$ will depend on unknown parameters $\vec{X}_n$. The estimation $\hat{\vec{X}}_n$ of vector $\vec{X}_n$ in (5) within each of the n-th time interval $[t_{n-1}, t_n]$ being optimum from the viewpoint of the maximum likelihood is characterized by the covariance matrix:

$$E\left\{\hat{\vec{X}}_n \hat{\vec{X}}_m^*\right\} = G_{nn}^{-1} G_{nm} G_{mm}^{-1}, \tag{6}$$

where G is the Fisher information matrix [7]; $E\{\cdot\}$ is the operation symbol of calculating the mathematical expectation. Therefore, $\mathrm{var}\left(\hat{\vec{X}}_n\right) = G_{nn}^{-1}$. If we assume that the size of the observation interval T to be significantly greater than the interval of signal and noise correlation, then the realization of the observed signal by a set of harmonics can be rightly represented in the form:

$$\vec{r}_n = \left(r_n^1(\omega_1), r_n^2(\omega_1), r_n^1(\omega_2), r_n^2(\omega_2), ...\right)^T. \tag{7}$$

Using (7) the correlation relation between the separate signal components of the receiving elements can be obtained:

$$E\left\{r_n^i(\omega_k) r_m^{*j}(\omega_l)\right\} = \frac{e^{-j\omega_k t_n + j\omega_l t_m}}{T} \cdot \iint_T r_{i,j}(t + t_n, \tau + t_m) e^{-j\omega_k t_n + j\omega_l t_m} dt d\tau, \tag{8}$$

where $r_{i,j}(t,\tau)=E\{r_i(t),r_j(\tau)\}$.

Let us consider the case when $i=1,\ j=2$. From (2), (3) it follows that

$$r_{1,2}(t,\tau')=R_S(t-\tau'+\Delta\tau(\tau')), \tag{9}$$

where $R_S(\cdot)$ is the correlation function of the signal.

In the general case, the components $R_S(\cdot)$ depend not only on the difference $(t-\tau')$, but on the values t and τ' themselves. However for the special case, when $\Delta\tau=0$, we can write:

$$r_{i,j}(t,\tau')=R_S(t-\tau')+R_{ni}(t-\tau')\delta_{ij}, \tag{10}$$

where R_{ni} is the correlation function of the noise at the output of the i -th antenna, δ_{ij} is the Kronecker delta. Hereafter we assume that $r_{i,j}(\tau')$ can be represented as

$$r_{i,j}(\tau')=\frac{1}{2\pi}\int_{-\infty}^{\infty}S_{ij}(\omega)e^{j\omega\tau'}d\omega \tag{11}$$

in the chosen interval. Here $S_{ij}(\omega)$ is the mutual spectrum between the i -th and the j -th receiving elements.

Substituting (10) and (11) into (8) and performing evident transformations, we obtain:

$$E\{r_n^i(\omega_k)r_m^{*j}(\omega_l)\}=\frac{T}{2\pi}\int_{-\infty}^{\infty}S_{ij}(\omega)F_n^*(\omega-\omega_k)F_m(\omega-\omega_l)d\omega, \tag{12}$$

where $F_m(\omega-\omega_k)=\dfrac{\sin((\omega-\omega_k)T/2)}{(\omega-\omega_k)T/2}e^{-j(\omega-\omega_k)t_k}$.

Since the changes of the signal and noise spectral density within the chosen time interval pass smoothly without jumps, the integral in Expression (12) may be calculated in a simplified way:

$$E\{r_n^i(\omega_k)r_m^{*j}(\omega_l)\}=\frac{T}{2\pi}S_{ij}\left(\frac{\omega_k+\omega_l}{2}\right)\int_{-\infty}^{\infty}F_n^*(\omega-\omega_k)F_m(\omega-\omega_l)d\omega=$$

$$=TS_{ij}\left(\frac{\omega_k+\omega_l}{2}\right)\int_{-\infty}^{\infty}F_T(t-t_n)F(t-t_m)e^{-j(\omega_k+\omega_l)t/2}dt, \tag{13}$$

where

$$F_T(t)=\begin{cases}1, at\ |t|\le T/2\\ 0, at\ |t|\ge T/2\end{cases}. \tag{14}$$

Using the Parsifal Theorem [8] we substitute (14) in (13) and perform integration to obtain:

$$E\{r_n^i(\omega_k)r_m^{*j}(\omega_l)\}=TS_{ij}\left(\frac{\omega_k+\omega_l}{2}\right)\frac{\sin\left[(\omega_k-\omega_l)(T-|t_n-t_m|)/2\right]}{(\omega_k-\omega_l)T/2}e^{-j(\omega_k+\omega_l)(t_n-t_m)/2} \tag{15}$$

for $|t_n-t_m|\le T$; and

$$E\{r_n^i(\omega_k)r_m^{*j}(\omega_l)\}=0 \tag{16}$$

for $|t_n-t_m|\ge T$.

The meaning of condition (16) lies in the fact that r_n and r_m are obtained from the counts of the received signals which do not overlap. With reference to condition (16) it follows that the correlation function $E\left\{\hat{\vec{X}}_n\hat{\vec{X}}_m^*\right\}$ of estimations of vector $\vec{X}$ equals to zero for indexes $n\ne m$. Therefore, the relationship (15) is simplified for the case $n=m$ and takes the form

$$E\left\{r_n^i\left(\omega_k\right)r_m^{*j}\left(\omega_l\right)\right\}=S_{ij}\left(\frac{\omega_k+\omega_l}{2}\right)\cdot\frac{\sin\left[\left(\omega_k-\omega_l\right)T/2\right]}{\left(\omega_k-\omega_l\right)T/2}e^{-j\left(\omega_k+\omega_l\right)t_n/2}. \quad (17)$$

Let us denote $\omega_k=\left(2\pi/T\right)k$. Then the second multiplier in Formula (17) is reduced to the following expression:

$$\frac{\sin\left[\left(\omega_k-\omega_l\right)T/2\right]}{\left(\omega_k-\omega_l\right)T/2}=\frac{\sin\left(\left(k-l\right)\pi\right)}{\left(k-l\right)\pi}=\delta_{kl}. \quad (18)$$

Substituting (18) in (17) we obtain:

$$E\left\{r_n^i\left(\omega_k\right)r_m^{*j}\left(\omega_l\right)\right\}=S_{ij}\left(\omega\right)\delta_{kl}. \quad (19)$$

The desired values of the parameter estimations $\Delta\tau_n$, $\Delta\dot{\tau}_n$ which meet the criterion of the likelihood maximum can be obtained using the means of the calculus of variations [9]:

$$\frac{\delta}{\delta\Delta\tau_n}E\left\{r_n^i\left(\omega_k\right)r_m^{*j}\left(\omega_l\right)\right\}\Bigg|_{\Delta\tau(t)=0}=\left(j\right)^{i-j}\omega_k S\left(\omega_k\right)\delta_{kl}\left(1-\delta_{ij}\right), \quad (20)$$

$$\frac{\delta}{\delta\Delta\dot{\tau}_n}E\left\{r_n^i\left(\omega_k\right)r_m^{*j}\left(\omega_l\right)\right\}\Bigg|_{\Delta\tau(t)=0}=\frac{\left(-1\right)^{k-i}}{4\pi\left(k-l\right)}\left[\omega_k S\left(\omega_k\right)+\omega_l S\left(\omega_l\right)\right]\left(1-\delta_{kl}\right)\left(1-\delta_{ij}\right), \quad (21)$$

where symbol $\left(j\right)$ in Formula (20) means the imaginary unit.

The solution of set of Equations (20), (21) in view of Equation (19) makes it possible to obtain the expression for the dispersions of estimations $\Delta\hat{\tau}_n$, $\Delta\hat{\dot{\tau}}_n$ of the desired parameters $\Delta\tau_n$, $\Delta\dot{\tau}_n$. The dispersion values of the delay estimations and its derivative coincide with the values, which are determined by the Cramer-Rao boundary [7] and are the diagonal elements of the matrix G_{nn} in Expression (6). The analytic expression for the corresponding estimation of dispersion of parameters $\Delta\tau_n$, $\Delta\dot{\tau}_n$ with an accuracy of the constant multiplier C_x is determined as follows:

$$\sigma_x^2=C_x\int_0^\infty\frac{\omega^2\chi_i\chi_j}{1+\chi_i+\chi_j}d\omega, \quad (22)$$

where $C_x=T/\pi$ at $x=\Delta\hat{\tau}_n$, $C_x=T^3/12\pi$ at $x=\Delta\hat{\dot{\tau}}_n$; $\chi_{i(j)}=S\left(\omega\right)/N_{i(j)}\left(\omega\right)$.

IV. TECHNICAL REALIZATION AND CHARACTERISTICS

The simplified block diagram of the device realizing the algorithm of signal processing for two- position receiving system is shown in Fig. 1. The signals reflected from the target which is situated at the distance x_1 from the receiving antenna A_1 and at the distance x_2 from the receiving antenna A_2, are intensified by identical linear amplifiers r_1 and r_2 of the receiving system. Then spectral functions of the received signals are calculated in each channel using the algorithm of the fast Fourier transform as a base. After multiplication in the correlator, they enter the calculation block of the inverse Fourier transform and the integrator realizing in doing so the procedure of calculating the cross-correlative function. The value of the cross-correlative function maximum compared with the threshold makes it possible to make a decision about the presence or absence of the target in the given pulse volume. At the same time, the estimation of the position of the maximum of this function on the plane “delay-frequency” makes it possible to locate the target position in space. Subsequently, the Doppler signal spectrums of each channel are processed separately by comparing their modulating functions to reject the false responses and responses from disturbances. For example, it is important when identifying the objects which do not have a linear component of the speed vector, but oscillate periodically or perform rotary motions about some point.

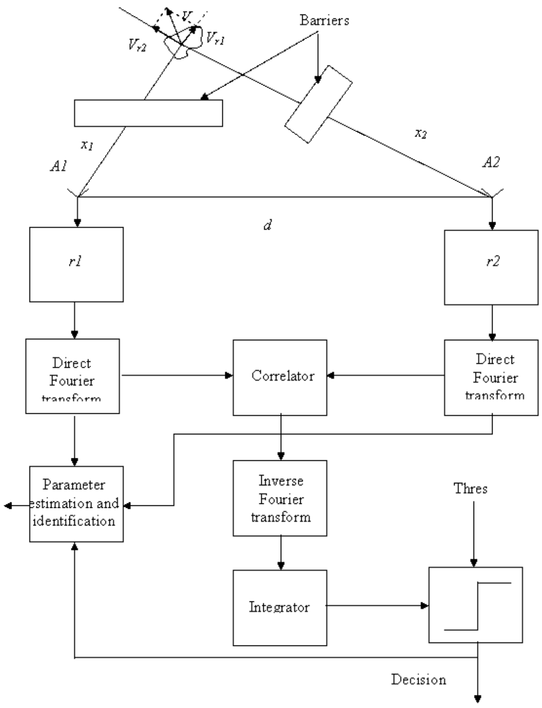

Fig. 1 The block diagram of the device realizing the signal processing algorithm of signals for two-position receiving system

Fig. 2 shows the cross-correlative function of the signals reflected from a single target with a harmonic Doppler modulation 0.5 Hz at carrier frequency 1 GHz. Analytic expression approximating this process can be written in the following form:

$$R(t_1,t_2) = a \cdot \exp\left(-\alpha\left|t_2 - t_1\right|\right) \cdot \left[\cos\left(\Omega\left(t_2 - t_1\right)\right) + \frac{\alpha}{\Omega}\sin\left(\Omega\left(t_2 - t_1\right)\right)\right], \tag{23}$$

where a, α are constant coefficients.

Fig. 3 shows the form of the cross-correlative function of the signals at Doppler modulation 2 Hz. As can be seen from the comparison of Fig. 2 and Fig. 3, the form of the cross-correlative function changes with the change in parameters of target movement, which can be used for target identification.

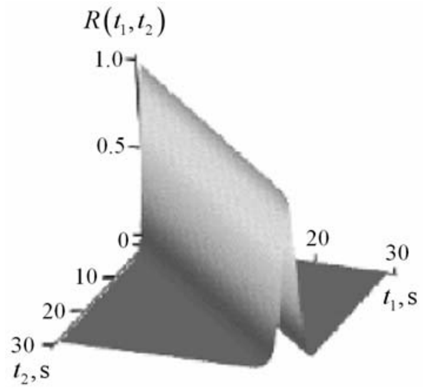

Fig. 2 The cross-correlative function of the signals reflected from a single target with the harmonic Doppler modulation 0.5 Hz

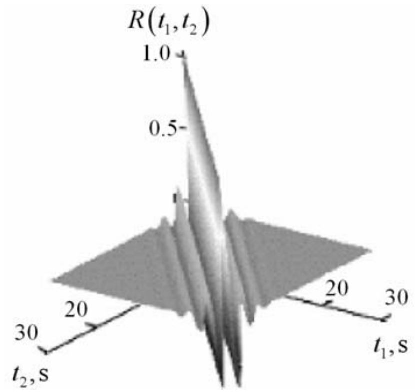

Fig. 3 The cross-correlative function of the signals reflected from a single target with the harmonic Doppler modulation 2 Hz

The operation efficiency of the algorithm substantially depends on the signal/noise relation. In particular, the probability P_D of a true detection of the object at the given level of false alarms P_F was calculated under the assumption that the signal is weak, which as a rule takes place in actual practice. In this case, the logarithm of the likelihood relation is distributed according to the normal law [7] and the decision capacity at the amplitude detection is well approximated by using the analytic expression of the following form:

$$P_D = 1 - \Phi\left(\frac{\ln(c)}{\sqrt{q}} - \sqrt{q}\right), \tag{24}$$

where $\Phi(z) = \frac{1}{2\pi}\int_{-\infty}^{z} e^{-\frac{1}{2}x^2}dx$ is the probability integral and $q = 2S(\Omega)/N(\Omega)$ is the signal/noise relation. The calculation results are presented in Fig. 4.

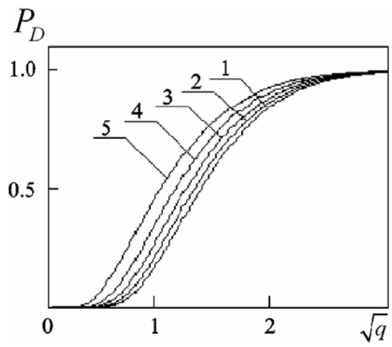

Fig. 4 Characteristics of detection

The detection characteristics have been calculated taking into account that the sounding signal is the phase-manipulated Myerson-code sequence having 1023 elements in length. Besides, the substitution of the signal frequency ω for the information process frequency Ω was carried out. This does not reduce the generality of results, because for the amplitude post-detection method of detection of the weak signal only the envelope sampling (counting) is used in the algorithm, which significantly simplifies the modeling.

The analysis of these characteristics shows that we cannot assume the algorithm under consideration to be the strongly optimum, because the sum of optimum solutions over all elementary areas “delay – the Doppler frequency shift” is not the optimum solution for the whole domain of signal existence. Nevertheless, the algorithm possesses sufficiently high characteristics concerning the detection and identification. In the special case when $\Delta\dot{\tau}_n = 0$ the solutions coincide with the optimum in the plane $[\Delta, \Omega]$.

V. CONCLUSIONS

Thus the considered approach based on the correlation-spectrum analysis of the signal readings of the spaced two-position receiving system makes it possible to obtain a quasi-optimal decision rule concerning the hypothesis about the presence of reflections from the target with the simultaneous estimation of the spaced position and parameters of its movement. The subsequent target identification is performed by investigating the shape and behavior of two-dimensional cross-correlative signal function over the whole domain of its existence. The character of movement, precession or fluctuation displacement of the object under investigation determines the individual features of the information process and is the basis for the decision that the object belongs to a certain class.

The application of the likelihood maximum method is due to the absence of information about the character of the initial information processes given a priory, which makes the algorithm more universal, but at the same time more intricate from the viewpoint of calculations. In the case when the object does not have the linear component of the speed vector i.e. the center of gravity of the object does not moves with respect to the receiving system antennas, but just oscillates periodically or performs rotary motion, the identification algorithm can be modified and it is possible to make adaptive one. For example, using the optimum estimation sequence as a basis, the estimation of the Doppler modulation law of the information process can be built, that can be further used in the procedure of the dynamic Kalman filtration to obtain refined estimations.

REFERENCES

[1] K. M. Chen, Y. Huang, J. Zhang, and N. Adam, (2000), IEEE Trans. Biomed. 47(l):105-114.

[2] The Doppler Radar for On-site Prospecting, (1997), VINITI, Moscow.

[3] V. S. Chernyak,, (1973), Radiotekhnika i Elektronika. 18(5):59-969 (in Russian).

[4] V. H. MacDonald, and P.M. Schultheiss (1969), J. Acoust. Soc. Amer. 46:37-43.

[5] Ye. Ye. Koltyshev, V. V. Petrov, and V. G. Yankovskii, (2002), Radiotekhnika I Elektronika. 5:15-21 (in Russian).

[6] R. K. Dikson (1979), Broadband Systems, Radio i Svyaz’, Moscow, (in Russian).

[7] B. R. Levin (1975), Theory of Radio Engineering Statistics, Sov. Radio, Moscow, (in Russian).

[8] Ango (1965), Mathematics for Electrical- and Radio Engineers, Nauka, Moscow, (in Russian).

[9] G. Korn, and T. Korn (1968), Mathematical Handbook, McGraw-Hill Book Company, New York.

[10] Voprosy podpoverhnostnoy radiolokatsii (2005) // Ed. A. Ur. Grinev. − Moscow.: Radiotehnika, (in Russian).

[11] I. A. Vyzmitinov, Y. I. Myroshnichenko, O. V. Sytnik, Y. A. Kopylov Design Problems of Rescue-Radar // Proc. of Intern. Conf. Antennas, Radar and Wave Propagation // ARP-2007, Montreal, QC. Canada. – 5/30/2007 – 6/1/2007. – Radar: 566-082.

[12] O. V. Sytnik, Y. I. Myroshnichenko, Y. A. Kopylov Radiophysics and Electronics (2002). 7 (3) − P. 548 – 554. (in Russian).

[13] Radar Handbook (1970) / Editor-In-Chief. M.I. Skolnik. − McGraw-Hall Book Company.

[14] O. V. Sytnik (2003) Radiophysics and Radioastronomy. Kharkov. 8 (2). − P. 199 − 206. (in Russian).

Oleg Sytnik was born in Dneprodzerginsk, Ukraine, on May 17, 1958. He received the M.S. degree in radio engineering from the Kharkov University of Radio Electronics, Kharkov, in 1980. He was working in the Design Bureau of Machine-Building Plant of Dnipropetrovsk (1980-1982), and then in the Radio Engineering Department of the Kharkov University of Radio Electronics (1982-1986). He received the Ph.D. degree in radars and navigation from the Kharkov University of Radio Electronics, Kharkov, in 1986. Since 1986 he has worked at the position of a senior scientist in the National Academy of Sciences of Ukraine Usikov’s Institute of Radiophysics and Electronics, Department of Radiophysical Introscopy and in the A.I. Kalmykov’s Center of Radiophysical Sounding of the Earth of National Academy of Sciences and National Cosmic Agency of Ukraine. During this time he has got Dr. Sci. degree in Radio Physics and Mathematics and Professor (2005). He has also published nearly 140 science papers in radars theory, digital signal processing and applications. His fields of science interests are radars, digital signal and image processing, pattern recognition and stochastic non stationary processes.