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Ivan F. Kupryashkin
Military Educational and Scientific Center of the Air Force
"N. E. Zhukovsky and Yu. A. Gagarin Air Force Academy"
54A, Starykh Bolshevikov Str., 394064, Voronezh, Russia
Natal'ya V. Sokolik✉
Information-Technical Center of the South Military Command
43, Budyonnovsky Pr., 344011, Rostov-on-Don, Russia

ALGORITHM OF SIGNAL PROCESSING IN THE RADAR SYSTEM WITH CONTINUOUS FREQUENCY MODULATED RADIATION FOR DETECTION OF SMALL-SIZED AERIAL OBJECTS, ESTIMATION OF THEIR RANGE AND VELOCITY

Abstract. *Nowadays the interest in search of ways of improving the efficiency of small radar cross-section aerial objects detection and localization rises against the background of widespread use of light and unmanned aerial vehicles. As a result, researchers pay attention to radar systems (RS) with continuous linear frequency modulation (linear FM) signal. The use of such signals gives the measurable opportunity to reduce radar system peak-speech power and to cut the cost and weight-size parameters of the RS. The paper observes low-power ground based radar implementation prospects for purposes of detection and estimation of motion rates of small-sized aerial objects. The proposed algorithm of radar signals processing enables to simplify the detection of such tar-gets. The paper reveals the structure and defines the steps of the algorithm. The fundamental for the algorithm under consideration is the method of the range-Doppler image composition of the scanned area using digital signal processing. The paper presents the results of the algorithm operation in the low-power RS of C-band radar, obtained by processing of quadrotor echo-signals during the real experiment. The results show successful solvation of the applied problem of detection and tracking on the small-sized aerial object with the radar cross-section equal to less than 0.5* m^2 *and the spectrum of secondary radiation characterized by the expressed multimodality. The results of the experiment validate the application of the algorithm and demonstrate the possibility of the algorithm implementation in design of portable RS and automated target acquisition centers for detecting and tracking of the small-sized aerial targets (both, single as multi agent) with the information display on operator control panel.*

Key words: radar system, signal processing, small-sized aerial objects, target return, range-Doppler image

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И. Ф. Купряшкин
Военный учебно-научный центр
"Военно-воздушная академия им. проф. Н. Е. Жуковского и Ю. А. Гагарина"
ул. Старых Большевиков, д. 54А, Воронеж, 394064, Россия
Н. В. Соколик✉
Информационно-технический центр Южного военного округа
пр. Буденновский, д. 43, Ростов-на-Дону, 344011, Россия

АЛГОРИТМ ОБРАБОТКИ СИГНАЛОВ В РАДИОЛОКАЦИОННОЙ СИСТЕМЕ С НЕПРЕРЫВНЫМ ЧАСТОТНО-МОДУЛИРОВАННЫМ ИЗЛУЧЕНИЕМ В ИНТЕРЕСАХ ОБНАРУЖЕНИЯ МАЛОЗАМЕТНЫХ ВОЗДУШНЫХ ОБЪЕКТОВ, ОЦЕНКИ ИХ ДАЛЬНОСТИ И СКОРОСТИ ДВИЖЕНИЯ

Аннотация. *На фоне повсеместного использования беспилотных летательных аппаратов и легкомоторной авиации растет интерес к поиску путей повышения эффективности локализации и определения параметров движения воздушных объектов с малой эффективной площадью рассеяния. В связи с этим закономерно внимание к радиолокационным системам (РЛС) с непрерывным линейно-частотно-модулированным (ЛЧМ) излучением. Использование таких зондирующих сигналов позволяет значительно снизить пиковую мощность РЛС и уменьшить ее массогабаритные и стоимостные характеристики. Статья посвящена исследованию перспективы применения маломощной наземной РЛС с непрерывным ЛЧМ-сигналом в интересах обнаружения, а также определения координат и параметров движения малозаметных воздушных объектов. Предложен алгоритм обработки радиолокационных сигналов, позволяющий упростить процедуру обнаружения таких целей, раскрыта структура и приведено описание этапов алгоритма. В основе рассматриваемого алгоритма лежит методика формирования дальностно-доплеровского портрета зоны обзора с использованием цифровой обработки сигнала. Приведены результаты применения алгоритма в маломощной РЛС С-диапазона, полученные при обработке эхосигналов квадрокоптера, зарегистрированных в ходе натурного эксперимента. Показано успешное решение практической задачи обнаружения и сопровождения малоразмерного воздушного объекта с эффективной площадью рассеяния до 0.5 м^2, спектр вторичного излучения которого характеризуется выраженной многомодальностью. Результаты эксперимента подтвердили практическую значимость предлагаемого алгоритма и возможность его реализации при создании мобильных переносных радиолокационных комплексов и постов автоматического обнаружения и сопровождения малозаметных одиночных и групповых целей с выдачей информации на пульт оператора.*

Ключевые слова: радиолокационная система, обработка сигналов, малоразмерная воздушная цель, эхосигнал, дальностно-доплеровский портрет

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Introduction. Detection of small-sized aerial objects (light-engine aircrafts, helicopters and drones) is one of the most important tasks of modern radioelectronic surveillance systems [1]. The significant growth in manufacturing of small-sized aerial vehicles and the increase in the degree of threats caused by their widespread determine the relevance of the problem. At the same time, selection and determination of such targets motion rates against the background of clutter is a challenging task [2].

Recently, researchers pay significant interest to the radar systems (RS) with continuous linear-frequency-modulated probing signal [2]–[5], since the use of this signal gives the opportunity to reduce the peak power of RS radiation, and, as a result, to decrease the energy consumption and improve the mass-dimensional and cost characteristics of the system.

Researchers usually characterize small-sized aerial objects by radar cross-section of the order of 0.001...0.1 m^2 [6]–[8]. This characteristic in case of the continuous relatively low radar power (0.01...1 W) leads to the requirement to increase the echo-signal coherent integration time in order to provide the quality of the target detection. However, the echo-signals of such objects, as for instance multi copters, are characterized by Doppler frequency spectrum multimodality [6], [7]. This fact significantly complicates the target velocity determination using traditional approaches applied in pulse-Doppler radars.

Consequently, the purpose of the paper is to create signal processing algorithm for the continuous radiation radar, providing an effective filtering of echo-signals of small-sized aerial objects on the background of clutter and ambient noise.

Description of the algorithm. Continuous wave RS block diagram (Fig. 1) includes the transmitting unit (TU), the receiving unit (RU), the mixing unit

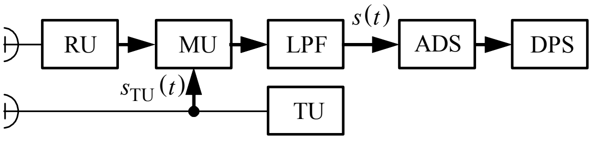

Fig. 1. Block Diagram of a Radar System with Continuous Linear FM-Signal

(MU), the low-pass filter (LPF), analog-to-digit converter (ADC) and digital signal processing system (DPS). Continuous wave radar system using the proposed algorithm of processing of the received signals includes the following main steps:

– formation and radiation of the probing signal;

– echo reception and demodulation of the probing signal;

– conversion of the received signal into digital form;

– discrete Fourier transformation (DFT) of the signal samples recorded during the given coherent accumulation time interval (formation of the set of complex long-range portraits of the viewing area);

– clutter filtering;

– selection of target echo targets in the range-Doppler image using the adaptive detector of local inhomogeneity;

– inter-period average signal amplitudes in individual range channels.

Below the steps of the signal processing algorithm on the example of the isotropic point reflector are considered.

Formation and emission of the probing signal. The signal generated by the RS transmitter with continuous radiation and emitted during a separate sensing period T can be described by the following correspondence

$$s_{\text{TU}}(t)=A_0\cos\left[2\pi f_0 t+(b/2)t^2+\psi_0\right],\ t\in[0;\ T],$$

where A_0 – is the probing signal amplitude; f_0 – is the initial frequency; $b=2\pi\Delta f_{\text{S}}/T$ – is the speed of the frequency change; Δf_{S} – is the signal bandwidth; ψ_0 – is the initial phase.

Receiving and demodulation of the echo-signal. The received echo-signal is multiplied with the reference one in MU (Fig. 1), and then, as a result of LPF filtering, the differential frequency signal is generated.

The equation below identifies the LPF cutoff frequency

$$f_{\text{cut}}=R_{\max}/C_r,$$

where $R_{\max}$ – is the restriction on the far edge of the RS area; $C_r=cT/(2\Delta f_{\text{S}})$ – is the coefficient of conversion values of the distance to the target in the corresponding values of the difference frequency; c – is the speed of light.

The LPF output signal is defined as follows:

$$s(t)=A_0\cos\left[2\pi f_0\tau(t)+b\tau(t)t-\right.$$
$$\left.-(b/2)\tau^2(t)+\psi_0\right],\ t\in[0;\ T],$$

where $\tau(t)=2R(t)/c$ – time delay; $R(t)$ – is the law of change distance between the radar and the target.

In the most practical cases, it is able to neglect the change in echo delay time during the modulation period. Then demodulated echo-signal is described on the n-th probing by the simplified expression:

$$s_n(t)=A_0\cos\left(2\pi f_{\text{d}n}t+\psi_n\right),\qquad(1)$$
$$t\in[0;\ T],\ n=\overline{1,\ N_f},$$

where $f_{\text{d}n}=b\tau_n/(2\pi)$ – is the demodulated return difference frequency of the echo-signal; $\psi_n=2\pi f_0\tau_n+\psi_0$ – is the initial phase, $\tau_n=2RnT/c$ – the return time delay at the beginning of the n-th probing; $N_f=T_0/T$ (T_0 – coherent integration time).

The conversion of the obtained signal into digital form. The sampling frequency of the demodulated return signal with its analog-to-digital conversion is chosen according to the classical relation [6] $F_{\text{ADS}}=2f_{\text{cut}}$. After sampling and memorizing in DSP memory (Fig. 1) the demodulated signal contributes a two-dimensional array of readouts of the form

$$S=\{s_{i,n}\};\ s_{i,n}=s_n(t_i),\qquad(2)$$
$$i=\overline{0,\ N_{\text{c}}-1},\ n=\overline{0,\ N_f-1},$$

where $t_i=i\Delta t=i/F_{\text{ADS}}$; $N_{\text{c}}=F_{\text{ADS}}T$.

Formation of complex set of range images of the scanned area. The following equation forms the 2D range image by the following equation:

$$\dot{S}_r=F_{||}\{S;\ K_r\},\qquad(3)$$

where $F_{||}\{\cdot\}$ – is DFT operator implemented with the frequency interpolation coefficient K_r over all N_f columns of the two-dimensional discretized echo-signal readings S (2), registered during the coherent integration time T_0.

The ratio below describes the spectrum of the echo-signal (1) received in the separate probing period

$$\dot{S}_r(f)=\frac{A_0T}{2}\left|\frac{\sin\left[\pi T\left(f_{\text{d}n}-f\right)\right]}{\pi T\left(f_{\text{d}n}-f\right)}\right|\times$$
$$\times\exp\left\{j\left[\pi T\left(f_{\text{d}n}-f\right)\right]+\psi_n\right\}.\qquad(4)$$

The equation determines the spectrum of the echo-signal radar range images in the following form:

$$\dot{s}_{r_{n,k}}=\frac{A_0T}{2}\left|\frac{\sin\left[\pi T\left(f_{\text{d}n}-f_k\right)\right]}{\pi T\left(f_{\text{d}n}-f_k\right)}\right|\times$$
$$\times\exp\left\{j\left[\pi T\left(f_{\text{d}n}-f_k\right)\right]+\psi_n\right\},$$

where $f_k=k\delta f_{\text{d}}=k/(K_rT)$, and $\delta f_{\text{d}}=1/(K_rT)$ – spacing of the difference frequency changing on the radar range image.

Formation of the range-Doppler image of the scanned area. It follows from (4) that the position of the maximum of the spectrum corresponds to the difference frequency of the demodulated signal, with the harmonic phase at this frequency being determined by the time delay of the echo-signal at the *n*-th sounding. Then, the average value of the Doppler frequency change over the observation interval is determined by the ratio of the phase increment to the signal modulation period:

$$f_{\mathrm{D}n} = \left(\psi_n - \psi_{n-1}\right) / (2\pi T).$$

Range-Doppler scanned area image is derived by performing

$$\dot{S}_f = F_{=}\left\{\dot{S}_r;\ K_f\right\}, \qquad (5)$$

where $F_{=}\{\cdot\}$ – is the DFT operator performed with the frequency interpolation coefficient K_f[1] over all N_r lines of the two-dimensional array of distance image readouts $\dot{S}_r$ (3) registered during the coherent integration time.

Based on the estimation of the echo-signal of two-dimensional spectrum envelope peak position (i.e. determining of the number of its row *k* and *m* column of the range-Doppler image) it is possible to proceed to the estimation of the target distance and velocity

$$\hat{R} = C_r\left(f_{\mathrm{d}k} - f_{\mathrm{D}m}\right);\ \dot{v}_r = -f_{\mathrm{D}m} c / \left(2 f_0\right), \qquad (6)$$

where $f_{\mathrm{D}m} = \left(m - K_f N_f / 2\right) \delta f_{\mathrm{D}}$ – is the Doppler frequency shift of the target return, and $\delta f_{\mathrm{D}} = 1 / \left(K_f T_0\right)$ – Doppler frequency step value on the range-Doppler image.

Clutter filtering. Before the implementation of the frequency peaks search procedure (finding *k* and *m* indexes) the spectral components located in the area of Doppler frequency shifts zero values should be rejected to avoid detection and estimation of parameters of the echo-signal of stationary reflectors.

Works [9], [10] note that the spectral power density envelope of passive clutters accurately approximates by the exponential model:

$$S_{\mathrm{pc}}(f) = \frac{1}{\sqrt{2}\sigma_f} \exp\left(\frac{\sqrt{2}|f|}{\sigma_f}\right),$$

where $\sigma_f = 2\sigma_v / \lambda$, and σ_v – is the mean square value of the passive reflectors velocity (from 0.12 m/s in case of light wind to 0.37 m/s in case of storm); $\lambda = c / f_0$.

Taking into account estimation (6) clutters can be rejected by alternately multiplying the array $\dot{S}_f$ elements (5) with readouts vector **U**. **U** elements can be defined as

$$U_m = 1 - \sqrt{\exp\left(\frac{\sqrt{2}\left|f_{\mathrm{D}m}\right|}{\sigma_f}\right)}.$$

Selection of echo-signal marks on the range-Doppler image. The frequency peaks adaptive detection can be carried out using a Constant False Alarm Rate (CFAR) detector [11]–[13]. CFAR operates (in general terms) to analyze the readouts localized within a rectangular moving area (Fig. 2).

Fig. 2, *3* show the detection of threshold determination based on readouts of density distribution estimation in background reflection zone. In case of sufficient statistic value determined by the readouts of the tested zone (Fig. 2, *1*) exceeds the threshold value, the algorithm takes the decision to detect the target.

The expected range of air vehicles velocity determines the test zone dimensions. The algorithm determines the minimum length at the range as

$$n_r = (1.3\ldots1.5)\Delta R_{\max} / \left(C_r \delta f_{\mathrm{d}}\right),$$

and at the Doppler shift as

$$n_{\mathrm{D}} = (1.3\ldots1.5)\left(2 f_0 \Delta v_{\max}\right) / \left(c \delta f_{\mathrm{D}}\right),$$

where $\Delta R_{\max} = v_{\max} T_0$ – is the change of the distance between the radar and the object moving with the maximum velocity $v_{\max}$, during the coherent integration time T_0; $\Delta v_{\max}$ – is the maximum change of the object radial velocity (the object is moving at the maximum velocity $v_{\max}$, at the same coherent integration time).

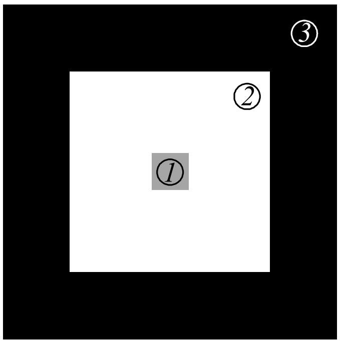

Fig. 2. CFAR Algorithm Operating Space

The size of the critical zone is selected (Fig. 2, *2*) to exclude the influence of target marks on the result of the parameters estimation of readouts density distribution in the zone of background reflections [13].

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[1] Frequency interpolation coefficients K_r and K_f determine the number of digital readouts per spectral component. The values range from 1...8 are determined by the performance of the DSP device and the required detailing of the range-Doppler image.

S*ignal amplitudes period averaging in separate range channels.* The main feature of the range-Doppler image of small-sized aerial objects (mainly multicopters) is Doppler frequency spectrum multimodality [6], [7]. As a result, the precise target velocity determination is difficult due to significant ambiguity of Doppler frequency shift of the target echo-signal.

In this situation, it is rational to use CFAR-detector not for the precise target mark locating, but to suppress range-Doppler image areas, in which the signal level did not exceed the threshold one. Further incoherent summation of the columns (which envelope range-Doppler images in separate channels), allows forming the averaged one-dimensional scanned zone range portrait:

$$\bar{S}_k = \frac{1}{N_f K_f} \sum_{m=0}^{N_f K_f - 1} \left| \tilde{S}_{f_{k,m}} \right|,$$

where $\tilde{S}_f = \left\{ \tilde{S}_{f_{k,m}} \right\}$ – is the range-Doppler image of scanning zone of the readouts after implementation of suppression procedures of clutter and background noise.

Fig. 3. Appearance of the Quadrotor Used In the Experiment

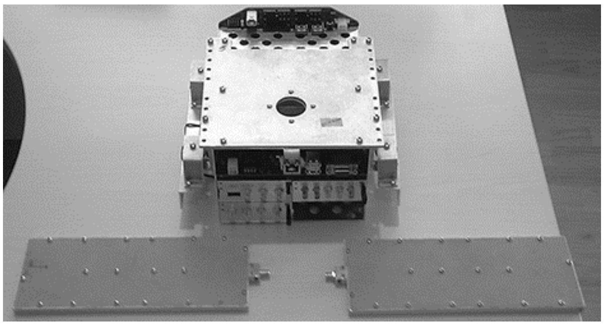

Fig. 4. Appearance of the Radar Used in the Quadrotor Detecting Experiment

Results of the experiment. Researchers from N. E. Zhukovsky and Y. A. Gagarin Air Force Academy together with the researchers from the Research institute of telecommunication technologies (Smolensk) carried out the described processing algorithm in the experiment (Fig. 3) to detect the quadrotor (Fig. 3). The Table shows the radar parameters.

Fig. 5 presents the example of the range-Doppler image of radar scanning zone. The bright vertical stripe is caused by the clutter. Fig. 6 shows the range profile correspondent to this portrait averaged over the observation interval $T_0 = 0.24$ s.

Fig. 7 shows the range-Doppler image of the observation sector after the rejection of clutters (the result

Radar basic specifications

Parameter	Specifications
Wavelength, cm	5.47 (C-band)
Radiated signal power, W	1
Signal spectrum width, MHz	475
Modulation period *T*, µs	1200
Maximum range, km	4
Weight, kg	4
Polarization	HH, VV, VH, HV

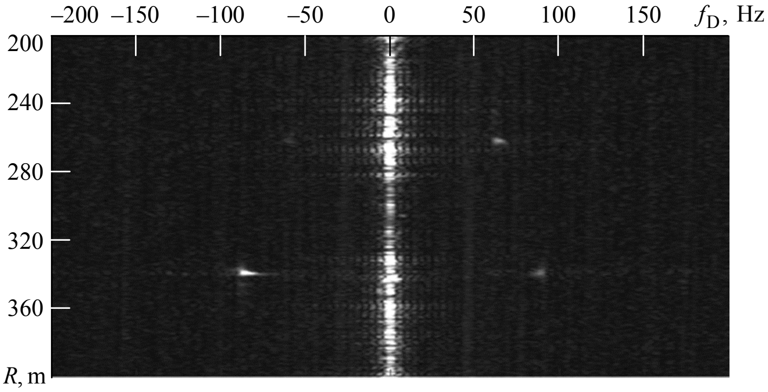

Fig. 5. Range-Doppler Image of Scanned Area before Clutter Rejecting

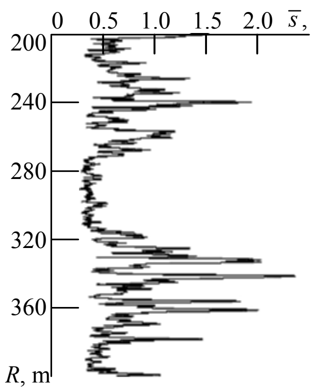

Fig. 6. Averaged Range Image before Clutter Rejecting

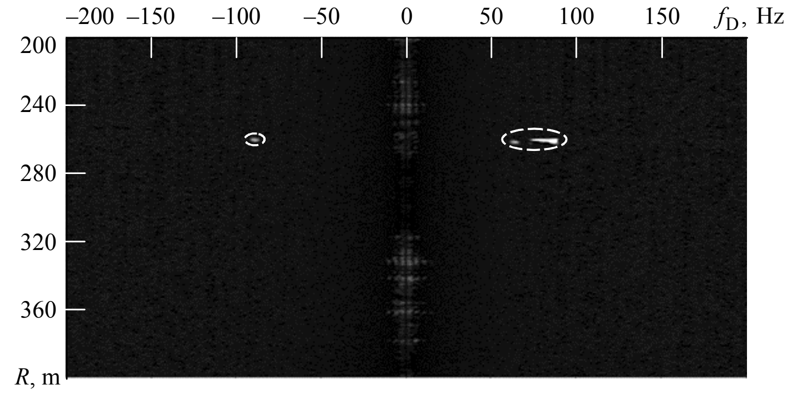

Fig. 7. Range-Doppler Image of Scanned Area after Clutter Rejecting

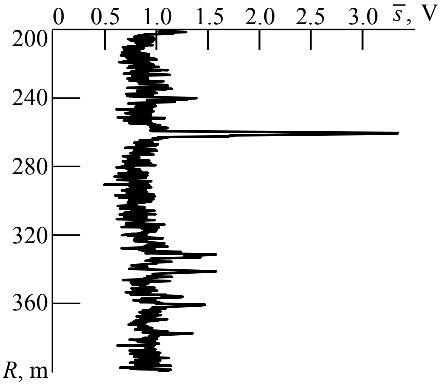

Fig. 8. Averaged Range Image after Clutter Rejecting and Quadrotor Discrimination

of filtering at $\sigma_v = 0.2\ \text{m/s}$), Fig. 8 shows the correspondent to this image range profile averaging during the $T_0 = 0.24$ s interval.

All range-Doppler images of the radar field of view (Fig. 5 and 7) have a horizontal band of varying intensity at a fixed range, generated by the Doppler components of the echoes of the quadrocopter rotating screws. The presence of such a mark can be considered as an informative sign of as a multikopter.

Further processing of the averaged range image can include target range detection and evaluation. Determination of velocity in this case bases on the estimation of target range mark shift in time between nearby intervals of coherent integration, i.e. with the traditional methods of radar signals secondary processing [14], [15]. The disadvantage of the approach is the inability to resolve same range targets by their Doppler shifts. However, if to consider that frequency band in modern radars with the continuous radiation is equal to hundreds of megahertz, i.e. that inclined range resolution is about a meter or better, this situation can be considered improbable or of a very short time.

Conclusion. Thus, in order to reduce the radiation power and, as a result, to increase the mobility, energy efficiency and secrecy of the ground-based radar, it is proposed to use continuous linear-frequency-modulated signals. The paper describes in detail the algorithm for processing of such signals, based on creating of the set of complex range images of the radar field on the interval of coherent accumulation of information with the further formation on this basis of the range-Doppler image of the observed sector of space. The subsequent rejection of the stable spectral components of the passive reflectors and selection of the target echo spectrum using the CFAR algorithm form the basis for the formation of the averaged range portrait of the radar area with the unique selection of the real targets on it.

During the field experiment using C-band radar with the average radiation power equal to 1 W, it was achieved the accuracy of determining the oblique range of the observed complex target with multimodal secondary radiation (quadrotor) up to 1 m, the radial velocity up to 1 m/s, and the possibility to determine the type of target was discerned.

The conducted field experiment showed the possibility of practical implementation of the described algorithm for processing continuous linear-frequency-modulated signals in order to effectively detect and determine the motion parameters of small-sized low-altitude aerial objects characterized by low radar visibility.

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Ivan F. Kupryashkin – Dr. of Sci. (Engineering) (2017), Assosiate Professor (2011) of the Departament of Combat Use of Electronic Warfare Systems (with Aerospace Control Systems and Guided Weapons) of Military Educational and Scientific Center of the Air Force "N. E. Zhukovsky and Yu. A. Gagarin Air Force Academy". The author of more than 100 publications. Area of expertise: radar systems; systems of radioelectronic counteraction to radar.
E-mail: ifk78@mail.ru

Natal'ya V. Sokolik – Dipl.-engineering (2001), Engineer in "Communication Networks and Switching Systems" of Novocherkassk Military Signal Institute. Head of the Department of the Information-Technical Center of the South Military Command (Rostov-on-Don). The author of 27 publications. Area of expertise: radar systems; radioelectronic systems; signal processing.
E-mail: sokolik777@mail.ru

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Купряшкин Иван Федорович – доктор технических наук (2017), доцент (2011) кафедры боевого применения средств РЭБ (с воздушно-космическими системами управления и наводящимся оружием) военного учебно-научного центра "Военно-воздушная академия им. проф. Н. Е. Жуковского и Ю. А. Гагарина". Автор более 100 научных работ. Сфера научных интересов – радиолокационные системы, системы радиоэлектронного противодействия радиолокационным системам.
E-mail: ifk78@mail.ru

Соколик Наталья Валентиновна – инженер по специальности "Сети связи и системы коммутации" (2001, Новочеркасский военный институт связи), начальник отделения Информационно-технического центра Южного военного округа (г. Ростов-на-Дону). Автор 27 научных работ. Сфера научных интересов – радиолокационные системы, радиоэлектронные системы, обработка сигналов.
E-mail: sokolik777@mail.ru
