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Determination of Fast-Moving Objects' Speed and Range with Linear Frequency Modulation Continuous Wave Radar Using Autocorrelation Scheme

Natal'ya V. Sokolik✉

Military unit 55060, Moscow, Russia

✉ sokolik777@mail.ru

Abstract

Introduction. Modern Advanced Driver Assistance Systems (ADAS) incorporate millimeter-range radars characterized by a relatively short range (meters – tens of meters). However, in order to meet the requirements of traffic safety, radar ranges should be increased to, at least, several hundred meters. This can be achieved by expanding the wavelength of a probing signal up to the centimeter range.

Aim. To develop an algorithm for estimating the range and speed of moving targets by radars based on a broadband continuous linear FM signal using an autocorrelation circuit. This algorithm can be used for increasing the speed of processing information by ADAS.

Materials and methods. The proposed algorithm is based on the methods of primary and secondary digital processing of radar signals. A simulation model of centimeter-range autocorrelation radar with a broadband continuous linear FM sounding signal was used to carry out practical experiments. The received signals were processed in the MatLab environment.

Results. This paper proposes an algorithm for determining the speed and range of fast-moving objects in cases where their movement during a certain observation interval exceeds significantly the radar range resolution. The use of a simplified Kalman filter for inter-period secondary signal processing allowed the stability of the algorithm to be significantly improved. Full-scale experiments using a low-power radar simulation model with continuous radiation of the centimeter range confirmed that the proposed algorithm provides a reliable assessment of the speed and range of a moving object at a distance of about one kilometer.

Conclusion. The obtained experimental results confirmed the robustness of the proposed algorithm even in the absence of inter-period secondary processing. The use of the latter will improve the stability of the algorithm without involving considerable additional computational costs, since the near-linear dynamics of the object under observation and the radar carrier allows a simplified Kalman filter in the form of an α - β -algorithm to be applied.

Keywords: ADAS, Radar System, Linear Frequency Modulation Continuous Wave Signal, Signal, Processing Algorithm, Autocorrelation Circuit

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Определение скорости движения и дальности быстро движущихся объектов в РЛС с непрерывным линейно-частотно-модулированным излучением с использованием автокорреляционной схемы

Н. В. Соколик✉

Войсковая часть 55060, Москва, Россия

✉ sokolik777@mail.ru

Аннотация

Введение. Аппаратную основу современных систем помощи водителю (ADAS) обычно составляют радиолокационные станции миллиметрового диапазона, характеризующиеся относительно небольшой дальностью действия (единицы–десятки метров). В то же время повышение безопасности движения требует ее увеличения как минимум до нескольких сотен, и одним из путей достижения таких значений является увеличение длины волны зондирующего сигнала, например переход в сантиметровый диапазон длин волн. В статье приведено подробное описание основных этапов работы алгоритма обработки сигнала в макете маломощной радиолокационной станции (РЛС) системы ADAS сантиметрового диапазона, обеспечивающего определение скорости движения и дальности быстро движущихся объектов.

Цель работы. Разработка алгоритма оценки дальности и скорости движения целей в РЛС с широкополосным непрерывным линейно-частотно-модулированным (ЛЧМ) сигналом на базе автокорреляционной схемы в интересах повышения скорости формирования оценок для системы ADAS.

Материалы и методы. Предлагаемый алгоритм базируется на методах первичной и вторичной цифровой обработки радиолокационных сигналов. Для проведения практических исследований использовался макет РЛС сантиметрового диапазона, собранной по автокорреляционной схеме, с широкополосным непрерывным ЛЧМ зондирующим сигналом. Для обработки зарегистрированной выборки отсчетов принятого сигнала применялась среда MatLab.

Результаты. Разработан алгоритм, обеспечивающий определение скорости и дальности быстро движущихся объектов в условиях, когда их перемещение за интервал оценивания существенно превышает разрешение РЛС по дальности. Использование упрощенной калмановской фильтрации для межпериодной вторичной обработки сигнала позволило существенно повысить устойчивость работы алгоритма. В ходе натурного эксперимента с использованием макета маломощной РЛС с непрерывным излучением сантиметрового диапазона показано, что устойчивая оценка скорости движения и дальности реального автомобиля обеспечивается на расстоянии как минимум порядка одного километра.

Заключение. Результаты проведенного натурного эксперимента позволили сделать вывод о высокой робастности предложенного алгоритма даже при отсутствии межпериодной вторичной обработки. Ее использование позволяет еще больше повысить устойчивость работы алгоритма при практически полном отсутствии дополнительных вычислительных затрат, так как близкий к линейному характер динамики объекта наблюдения и автомобиля-носителя РЛС позволяет полагать достаточным использование упрощенной реализации фильтра Калмана в форме α - β -алгоритма.

Ключевые слова: ADAS, радиолокационная система, непрерывный линейно-частотно-модулированный сигнал, алгоритм обработки сигналов, автокорреляционная схема

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Introduction. According to the Global Status Report on Road Safety [1] published by the World Health Organization, the number of road traffic accident (RTA) deaths in Russia amounted to 18 per 100 thousand people in 2018 compared to more economically developed EU countries. Thus, this parameter equaled 5.5, 4.1 and 2.8 for France, Germany and Sweden, respectively. Main causes of road accidents include traffic rule violations and insufficient driver qualifications.

European experience shows that advanced driver-assistance systems (ADAS) are effective in terms of improving road safety and reducing the impact of the human factor. At present, all car producers, not only in the premium car segment, equip vehicles with such systems. ADAS [2–4] incorporate technologies aimed at alerting the driver to potential problems, such as dangerous proximity to motorcyclists, cyclists and pedestrians. Among these technologies are the Front Collision Warning (FCW) and Pedestrian Collision Warning (PCW) systems.

The functions of such systems are implemented using radio detection and ranging (RADAR) technologies, whose radiation, unlike optical radiation, is practically not absorbed by the atmosphere or fog. Radar systems incorporated in ADAS should be capable of detecting and estimating the motion characteristics of high-speed objects, at the same time having small dimensions (size and weight) and a low power consumption from the automotive on-board network. To meet these requirements, it was proposed to use radars with a continuous linear frequency modulated (linear FM) signal [5–8].

Modern radars of this type provide continuous linear FM signals with a bandwidth of up to hundreds of megahertz and ensure their compression, thereby achieving a range resolution of up to several tens of centimeters. This allows the ratio of echo signals from an object to the background reflections to be significantly increased. However, the situations of high-speed approach (up to 100 m/s) require a short processing time (several milliseconds) for detecting a moving object in the resolution range, which makes it difficult to realize the coherent accumulation of the echo signals and, consequently, to achieve high quality in detecting and estimating the motion parameters of moving objects.

As shown in [9], an increase in the modulation period of the radiated continuous linear FM signal (from a few milliseconds for typical modern radars [10–12] to tenths of a second) in combination with

two-dimensional matched filtering methods results in a highly accurate estimate of the range and motion parameters for objects at a distance of several hundred meters, even at a small average radiation power (of the 10 mW order). However, the approach described in [9] sets strict requirements to the performance of the signal-processing device, which makes the entire system rather expensive.

Changes in the frequency of linear FM signals can be determined fairly straightforwardly using an autocorrelation circuit [13], which involves a relatively small amount of calculations. Given that the movement of a target causes the appearance of an additional linear frequency modulation in its echo signal [9], the method of autocorrelation can be used for constructing a device for obtaining speed and range estimates.

Aim. To develop an algorithm for estimating the range and speed of moving targets by radars based on a broadband continuous linear FM signal using an autocorrelation circuit. This algorithm can be used for increasing the speed of processing information by ADASs.

Operation of radars based on continuous linear FM signals. The block diagram of the radar [14] is provided in Fig. 1, where R is the receiver; T is the transmitter; M is the mixing unit; LPF is the low-pass filter; ADC is the analog-to-digital converter; DSP is the digital signal processing system. The functioning of this radar implies receiving an echo signal, its multiplying by the reference signal in the mixing unit, low-pass filtering of the multiplication result followed by its analog-to-digital conversion. The digital-signal processing (DSP) unit performs the procedure of detecting and evaluating the motion parameters of objects in the radar coverage zone according to the digital sampling of the demodulated signal received at the ADC output.

During a T modulation period, a radiated continuous linear FM signal can be described by the following expression [14]:

$$s(t) = A \cos\left(2\pi f_0 t + bt^2/2 + \psi_0\right) + \eta(t),$$

where $t \in [0; T]$; A is the signal amplitude; f_0 , ψ_0 are its initial frequency and initial phase, respective-

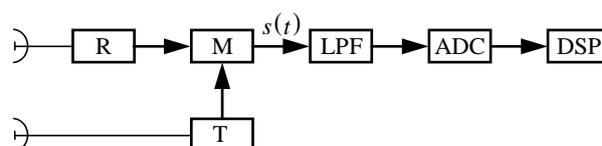


Fig. 1. Block Diagram of the Radar based on Linear Frequency Modulation Continuous Wave Signal

ly; $b = 2\pi\Delta f_c/T$ is the modulation coefficient (rate of frequency change for modulated signal); $\eta(t)$ is the implementation of the receiver noise; Δf_c is the bandwidth of the sounding signal.

After demodulation and low-pass filtering, the received echo of a moving object is described by the expression:

$$s(t) = A \cos \left[2\pi f_0 \tau(t) + b\tau(t)t - b\tau^2(t)/2 + \psi_0 \right] + \eta(t), \quad (1)$$

where $\tau(t) = 2R(t)/c$ is the echo delay due to the propagation to the object and vice versa with $R(t)$ law of the change in the distance between the radar and the object; c is the speed of light. The term $b\tau^2(t)/2$ is not taken into account in further calculations due to its negligible contribution to the resulting phase value.

Under a bandwidth equal to hundreds of megahertz, an object moving at a speed of v_r , during the T_0 observation interval is capable of moving a distance several times greater than the range resolution of Δr :

$$v_r T_0 \gg \Delta r = c/2\Delta f_c. \quad (2)$$

Since the duration of an individual sounding rarely exceeds hundreds of milliseconds, an assumption is made that the object is moving rectilinearly and uniformly ($R(t) = R_0 + v_r t$), and, thus, Eq.(1) can be re-written in the form of:

$$s(t) \approx A \cos(\theta_0 + \theta_1 t + \theta_2 t^2) + \eta(t);$$

where $\theta_0 = (4\pi f_0 R_0)/c + \psi_0$ is the unknown random initial phase of the signal, independent of the object speed; $\theta_1 = (2/c)(2\pi f_0 v_r + bR_0)$ and $\theta_2 = 2bv_r/c$ are the phase factors determined by the R_0 distance and the v_r radial speed of the observed object, respectively.

From the $\hat{\theta}_1$ and $\hat{\theta}_2$ estimates of the phase factors, estimates of the radial speed

$$\hat{v}_r = c\hat{\theta}_2/2b$$

and range are formed:

$$\hat{R}_0 = (c\hat{\theta}_1/2 - 2\pi f_0 \hat{v}_r)/b.$$

During autocorrelation, the rate of changes in the

frequency of a linear FM signal is calculated by multiplying the received signal with its delayed complex conjugate copy:

$$\begin{aligned} \dot{s}_c(t) &= [\dot{s}(t) + \dot{\eta}(t)] [s^*(t-\tau) + \eta^*(t-\tau)] = \\ &= A^2 \exp \left\{ j \left[(\theta_1 - \theta_2 \tau) \tau + 2\theta_2 \tau t \right] \right\} + \\ &+ A \exp \left[j \left(\theta_0 + \theta_1 t + \theta_2 t^2 \right) \right] \eta^*(t-\tau) + \\ &+ A \exp \left\{ -j \left[\theta_0 + \theta_1 (t-\tau) + \theta_2 (t-\tau)^2 \right] \right\} \dot{\eta}(t) + \\ &+ \dot{\eta}(t) \eta^*(t-\tau) \end{aligned} \quad (3)$$

where $\dot{s}(t) = s(t) + j\text{Hi}\{s(t)\}$; $\dot{\eta}(t) = \eta(t) + j\text{Hi}\{\eta(t)\}$, and $\text{Hi}\{\cdot\}$ is the Hilbert transform.

Based on (3), an estimate of the θ_2 quadratic phase factor is formed as follows:

$$\hat{\theta}_2 = \frac{2}{\tau} \arg \max_{\omega} \left(\int_0^T \dot{s}_c(t) \exp(-j\omega t) dt \right), \quad (4)$$

The practical implementation of procedure (4) includes the formation of a range image for the radar coverage with a subsequent step-by-step separation of spectral regions with a discretely increasing shift. Here, the radar coverage refers to a sector with an angular opening of 15–20°, a lower range of 5 m and an upper range of up to 800 m. The specified width of the selected spectrum parts is determined by a variation range of the difference frequency of an echo signal from an object moving at maximum permissible speed over a certain sounding period. After selecting the next spectrum part (in fact, band-pass filtering), the signal is fed to the input of the autocorrelation circuit. As a result, the radial speed of the high-speed objects under observation is obtained in accordance with (3) and (4). In this case, the assessment of the target range is determined by the current shift or, otherwise, by the lower boundary of the frequency band for the selected section in the echo signal spectrum.

Signal processing algorithm. *First stage.* The registration in the circuit memory of the DSP for the demodulated signal samples from the ADC output during the $T_0 \sim 1...2$ s observation interval (Fig. 2) is as follows:

$$s(i, n) = s(t_i - nT), \quad (5)$$

where $t_i = i\Delta t = i/F_{\text{ADC}}$; $i = \overline{1, N_r}$; $N_r = F_{\text{ADC}}T$,

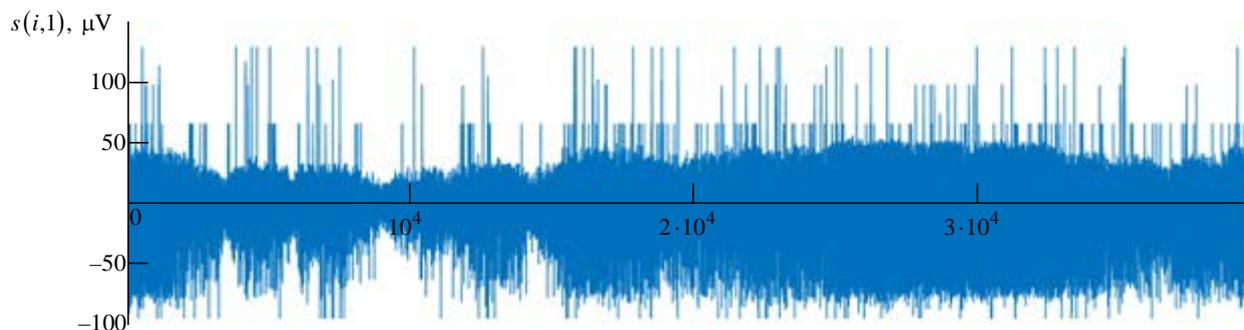


Fig. 2. Sampling of the Signal at The ADC Output Registered in the First Modulation Period

with $F_{ADC} \geq 2f_{LF}$ ADC sampling frequency; $f_{LF} = R_{max}/C_r$ is the cut-off frequency of the low-pass filter with the value determined based on a given upper coverage range of R_{max} ; $C_r = cT/2\Delta f_c$ is the conversion factor of the difference frequency values into the corresponding ones of the target range; $n = \overline{1, N_t}$; $N_t = \text{int}\{T_0/T\}$ is an integer number of radiation periods in the observation interval.

Second stage. Filtering of passive interference by rejecting zero Doppler components. To this end, a one-dimensional discrete Fourier transform (DFT) is performed on the lines of the signal array (5) with the formation of a complex Doppler image of the $\dot{\mathbf{S}}_0 = F\{\mathbf{s}_0\}$. monitoring zone. The frequency components of the image corresponding to the zero Doppler shift are assigned with zero values:

$$\dot{S}_f(i, n) = \begin{cases} 0, & n = 0; \\ \dot{S}_0(i, n), & n \neq 0. \end{cases}$$

Inverse DFT for the $\dot{\mathbf{S}} = F^{-1}\{\dot{\mathbf{S}}_f\}$ Doppler image lines provides for obtaining samplings of the complex received signals with suppressed background noise.

Third stage. Formation of a $\dot{\mathbf{S}}_r = F\{\dot{\mathbf{S}}\}$ complex

range-time image of the scanned area or a two-dimensional array of complex signals with the columns representing the spectra of echo signals in the sounding period and the column numbers corresponding to the numbers of the sounding periods. The complex range-time image (Fig. 3) is the result of a one-dimensional DFT of the $\dot{\mathbf{S}}$ array columns obtained after filtering the signal samples in each individual sounding period.

Fourth stage. Filtering of echo signals for observed objects. The procedure is carried out step by step. At each step, a filter with a jump-tunable pass band selects a section of the difference-frequency spectrum for the signal with the width of (as well as the filter pass-band) $\Delta f_r = v_{r,max}T/C_r$ determined by the maximum possible movement of the observed object during the sounding period. At each k -th step, the lower limit of the filter bandwidth (spectral component number) is determined by the expression of $n_{r_k} = \text{int}\{k\Delta R/\Delta r\}$, $k = \overline{1, N_k}$, where $\Delta R \approx (0.01...0.5)v_{r,max}T$ is the step of range determination (this value is set at the stage of determining the requirements for the accuracy of its estimation); $N_k = \text{int}\{R_{max}/\Delta R\}$. The number of filtered frequency spectrum discrete components is $M = \text{int}\{\Delta f_r C_r/\Delta r\}$.

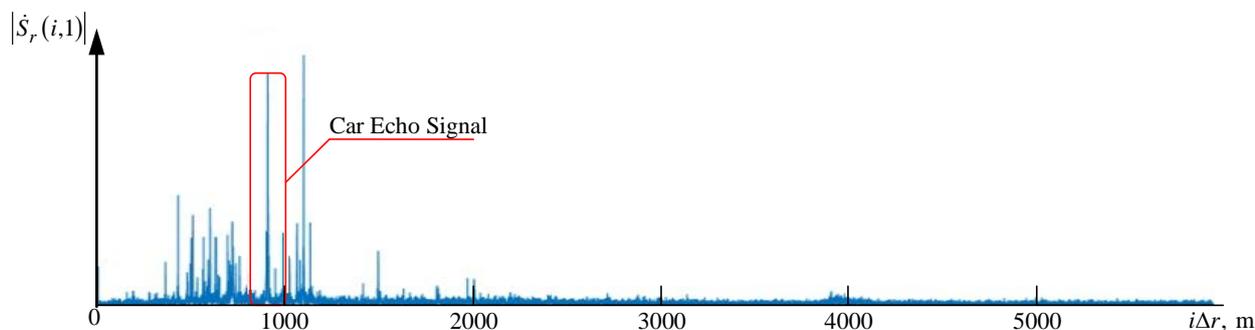


Fig. 3. The Range Image of the Scanned Area in the First Modulation Period

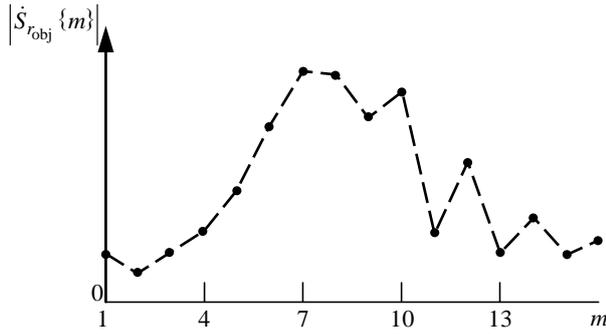


Fig. 4. Fragment of the Signal Spectrum Containing the Components of the Car Echo Signal (see Fig. 3)

The sampling of the filtered echo signals for the observed object located in the $k\Delta R \dots (k+1)\Delta R$, range is formed by calculating the inverse DFT:

$$[\dot{\mathbf{S}}_{\text{obj}}]_k = F^{-1} \left\{ [\dot{\mathbf{S}}_{r_{\text{obj}}}]_k \right\},$$

where $[\dot{\mathbf{S}}_{r_{\text{obj}}}]_k$ is a vector including M complex echo signal selected at the k -th step with $\dot{S}_{r_{\text{obj}}}\{m\} = \dot{S}_r\{n_{r_k} + m, n\}$, $m = \overline{1, M}$ (Fig. 4).

At each k -th step, the sampling of signals at the output of the autocorrelation circuit multiplier is formed as follows:

- a complex conjugate copy of the filtered echo signal sampling for the observed object is created;
- the created copy is shifted by the τ time relative to the original by the shift of $n_{\text{obj}} = \text{int}\{\tau/\Delta t\}$ signals to the right;
- the initial and complex conjugate samplings (Fig. 5) are multiplied elementwise:

$$[\dot{\mathbf{S}}_{\text{AC}}]_k = \dot{S}_{\text{AC}}\{m, k\} = \dot{S}_{\text{obj}}\{m\} \times \dot{S}_{\text{obj}}^*\{m - n_{\text{obj}}\}.$$

Fifth stage. Estimation of the radial speed and object range. At the fifth stage, the following procedures are consequently performed: calculating the envelope of the DFT image for the obtained sam-

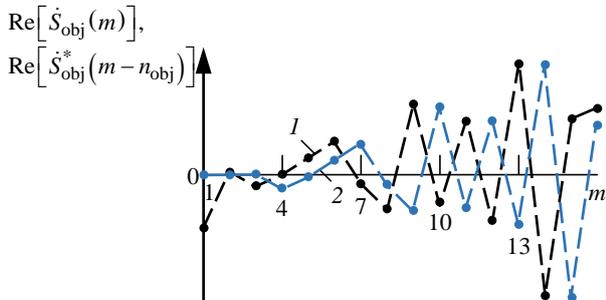


Fig. 5. Sampling of the Filtered Car Echo Signal (1) and its Shifted Copy (2)

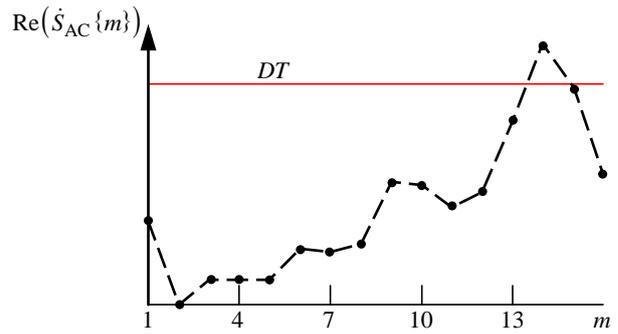


Fig. 6. Sampling of the Signal at the Output of the Autocorrelation Circuit Multiplier

pling of $[\dot{\mathbf{S}}_{\text{AC}}]_k$, comparing the maximum value of the obtained image with the detection threshold and estimating the position of the frequency sampling maximum in the case of exceeded threshold (Fig. 6). This procedure is equivalent to (4) and ensures the evaluation of the \hat{v}_{r_k} radial speed and the \hat{R}_{0_k} object range as:

$$\hat{v}_{r_k} = \frac{M}{N_r} \frac{\Delta r}{2\tau} \arg \max_m \left(\left| F \left\{ [\dot{\mathbf{S}}_{\text{AC}}]_k \right\} \right| \right);$$

$$\hat{R}_{0_k} = k\Delta R - \frac{C_r}{\Delta r} \frac{2\hat{v}_{r_k}}{\lambda},$$

where $\lambda = c/f_0$ is the wavelength of the radar sounding signal. Here, the radar radial speed resolution depends on the signal modulation period:

$$\Delta v_r = \lambda/2T. \quad (6)$$

The speed at which the observed object and the car approach one another includes the speed of movement for these objects. Therefore, the assessment of the real speed of the observed object can be calculated as the difference of the radial speed vector for the object and the vector of the car speed obtained from the on-board computer data.

The stages considered above characterize the option of primary signal processing in the radar under study.

The main task of secondary processing consists in the selection of true objects against the background of false detections. Provided that the duration of the sounding period remains constant throughout the entire observation interval and that the mutual approach (removal) of objects on the highway occurs without abrupt changes in speed, a versatile α - β filter can be used [15, 16].

In this case, the equations of extrapolation and the estimates of motion parameters for the observed

object are reduced to the following systems:

$$\begin{bmatrix} \hat{R}_{n+1|n} \\ \hat{v}_{n+1|n} \end{bmatrix} = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{R}_{n-1|n-1} \\ \hat{v}_{n-1|n-1} \end{bmatrix}$$

and

$$\begin{bmatrix} \hat{R}_{n|n} \\ \hat{v}_{n|n} \end{bmatrix} = \begin{bmatrix} (1-\alpha) & (1-\alpha)T \\ -\frac{\beta}{T} & (1-\beta) \end{bmatrix} \begin{bmatrix} \hat{R}_{n-1|n-1} \\ \hat{v}_{n-1|n-1} \end{bmatrix} + \begin{bmatrix} \alpha \\ \frac{\beta}{T} \end{bmatrix} \begin{bmatrix} \hat{R}_{0,k} \\ \hat{v}_{r,k} \end{bmatrix}$$

where the $n|n$ and $n-1|n-1$ indices denote the true values of the variables at n -th and the previous filtering step, respectively; the $n+1|n$ index is the extrapolation of the value to the next step.

Filter gains are independent of sounding noise and can be calculated as

$$K_R = \frac{2(2k-1)}{k(k+1)} \text{ and } K_v = \frac{6}{k(k+1)T}$$

for the range and the speed, respectively.

When designing a radar, the selection of the α and β coefficient values is based on the variances of the estimates for the range and the speed. In the case under consideration, when the fluctuations of these quantities are rather slow, the values of both coefficients should be selected in the range of 0.5–0.8.

Experimental study. In order to verify the operability of the proposed algorithm, a full-scale experiment was carried out using a real car and a radar with continuous linear frequency radiation of the centimeter range (frequency of $f_0 = 5.5$ GHz, signal bandwidth of $\Delta f = 500$ MHz, modulation period of $T = 0.1$ s) under an average radiation power of about 10 dBm. The radar was equipped with spaced receiving and transmitting antennas of a 18 dB gain. ADC sampling frequency was equal to $F_{\text{ADC}} = 400$ Hz, with an 8-bit resolution. No movement of the radar was performed during the experiment.

Since the full-scale experiment using the radar model was aimed exclusively at verifying the operability of the described primary processing algorithm, no justification of the radar characteristics related to the quality of target detection was performed.

After calculating the correlation sum of the signal sampling and its shifted copy, the DT detection threshold is calculated by the formula

$$DT = K_D \sum_{m \in M} A_m / M,$$

where $K_D = \pi \ln(F_D^{-1}) C(F_D, M) / 4$ is a constant with value selected based on the level of false alarms; F_D^{-1} is the given probability of a false alarm;

$A_m = \sqrt{A_{\text{obj}_m}^2 + A_{\text{obj}_{m-n_{\text{obj}}}}^2}$ is the amplitude of the correlation sum for the m -th element of the signal spectrum fragment. Figure 6 shows the result of the correlation sum for the $\text{Re}(\dot{S}_{\text{obj}}\{m\})$, $m = 16$ signal sampling and its $\text{Re}(\dot{S}_{\text{obj}}^*\{m - n_{\text{obj}}\})$, $n_{\text{obj}} = 1$ shifted copy, as well as its comparison with the set threshold.

The lines of the "slant range/radial speed" diagram (Fig. 7) are represented as the envelopes of the signal spectra at the output of the autocorrelation circuit (Fig. 8) obtained at various pass-band shifts of the extracting filter. An analysis of the diagram shows that the maximum signal is observed at a range of 918 m and a radial speed of about minus 10.6 m/s close to the car speedometer data (about 40 km/h). When performing the processing of the registered signal in the MatLab environment, the total time of diagram formation and that of obtaining the range and speed estimates turned out to be comparable with the duration of the sounding interval (about 1.2 s). Obviously, signal processing using the proposed software can be conducted in real time using even inexpensive small-sized on-board computing devices.

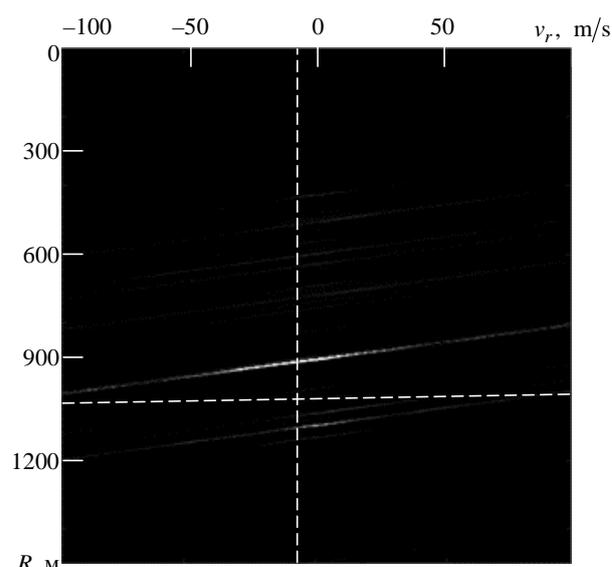


Fig. 7. The Resulting Diagram "Slant Range/Radial Speed"

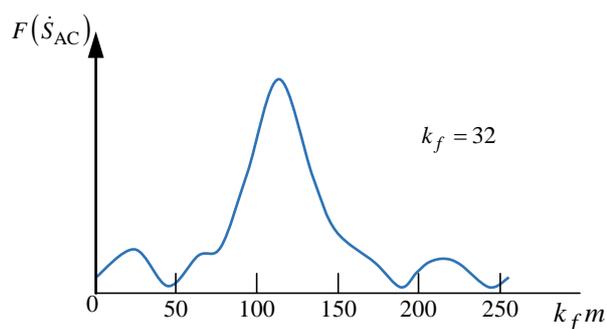


Fig. 8. Envelope of the Signal Spectrum at the Output of the Autocorrelation Circuit

Taking into account the nonlinear nature of processing information using radars with an autocorrelation circuit, the accuracy of such operations deserves additional research. Nevertheless, approximate accuracy estimates for determining the range and radial speed will be comparable with the resolving powers at the corresponding coordinates determined using (2) and (6), respectively.

Conclusion. By contributing to improved road safety, ADAS systems are increasingly used in today's automotive industry. In this article, an all-weather small-sized radar with continuous linear FM radiation is proposed as a technical basis for the de-

velopment of ADASs. The advantages of this radar type involve a relatively high quality of detection and estimation of motion parameters, a small weight and a low level of power consumption from the on-board automotive network. The use of the developed algorithm for estimating the range and speed of targets ensures a significant increase in the information processing performance of radars based on an autocorrelation circuit with broadband continuous linear FM sounding signal from the ADAS.

This article describes the main stages of the algorithm for primary signal processing by a radar with an autocorrelation circuit, as well as the results of a full-scale experiment confirming the feasibility of the proposed algorithm. The obtained experimental data showed that the developed algorithm is highly robust even in the absence of inter-period signal processing. Under a near-to-linear process of approaching the radar and the observed object, the problem of secondary processing the radar information can be solved using a conventional α - β filter [16] with coefficients from 0.5 to 0.8. The use of secondary inter-period signal processing will increase the stability of the algorithm under no additional computational costs.

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Information about the author

Natal'ya V. Sokolik, Dipl.-engineering on communication networks and switching systems (2001, Novocherkassk Military Communications Institute), Chief of the Department of the Military Unit 55060. Applicant for the Degree of Cand. Sci. in Military Educational and Scientific Center of the Air Force "N. E. Zhukovsky and Y. A. Gagarin Air Force Academy" (the Department of Combat Use of Electronic Warfare Systems (with Aerospace Control Systems and Guided Weapons)). The author of 29 scientific publications. Area of expertise: radar systems; radioelectronic systems; signal processing.

Address: Military Unit 55060, Moscow, Russia.

E-mail: sokolik777@mail.ru

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Информация об авторе

Соколик Наталья Валентиновна – инженер по специальности "Сети связи и системы коммутации" (2001, Новочеркасский военный институт связи), начальник отдела войсковой части 55060, соискатель ученой степени кандидата технических наук в военном учебно-научном центре "Военно-воздушная академия им. проф. Н. Е. Жуковского и Ю. А. Гагарина" (кафедра боевого применения средств РЭБ (с воздушно-космическими системами управления и наводящимся оружием)). Автор 29 научных работ. Сфера научных интересов – радиолокационные системы, радиоэлектронные системы, обработка сигналов.
Адрес: Войсковая часть 55060, Москва, Россия
E-mail: sokolik777@mail.ru
