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Correlated signal model for a velocity simulator of a correlation radar meter

One of the functions of a correlation radar meter for measuring altitude and velocity vector components is measuring the velocity vector components based on comparing correlation properties of the signals received by spatially separated antennae. The CRM test and control equipment contains a simplified velocity simulator forming signal transport delays according to the values of axial and transverse velocity vector components. We consider a correlated signal model allowing us to imitate a reflected signal that makes it possible to measure parameter values by means of transport delays and the difference in cross-correlation function maximum values.

Keywords: correlation radar meter, velocity simulator, correlated signal model

In the simplest case, the CRM velocity simulator is intended to form only signal transport delays which are traditionally used to determine parameters of longitudinal component V_x and lateral component V_z of the velocity vector. In addition to the above-mentioned correlation characteristics, the velocity simulator under consideration allows the following:

- shaping signals with the Gaussian distribution of oscillation amplitudes, the cross-correlation functions of which have the form nearly identical to real ones;
- changing the width of cross-correlation functions, thus simulating the flight over different underlying surfaces;
- setting given values of cross-correlation function maxima used for measuring parameter V_z by means of the amplitude method.

The study objective is to represent the results of development of a correlated signal model for the velocity simulator with the characteristics specified above.

Paper [1] describes theoretical fundamentals for developing a simulation model of the signal in the receiving channels of a correlation velocity meter as a whole, and the CRM velocity meter in particular. This paper proposes practical implementation of a correlated signal model for the velocity meter.

The most common model of the Earth's surface is supposed to be the superposition of a small-scale and large-scale continuous rough surface and objects, which can be represented as a system of discrete independent reflectors.

A radar signal reflected by the surface is a random process with spatially and time variable properties. Unlike the receiver self-noise, this process is spatially correlated. When an aircraft (A/C) flies over a non-uniform surface, the process in first approximation can be described by means of the Rayleigh distribution with time correlation, depending on the type of underlying surface. The Rayleigh process parameters such as mathematical expectation and form of the correlation function are time variables in accordance with the aircraft altitude and the type of underlying surface.

According to the CRM operation algorithm, the simulator shall shape three super-high frequency signals transmitted to the CRM receiving antennas. A signal transmitted to such antennas can be viewed as a high-frequency signal modulated by a low-frequency signal having random amplitude and phase.

A simulating random signal is shaped in accordance with the following algorithm:

- six random processes $x_1 \ldots x_6$ with uniform distribution are generated;
- based on obtained uniform processes, random processes with the Gaussian distribution $x_1', \ldots, x_6'$ are generated (two of them will be used for shaping two quadrature components of the desired signal; the other four random processes will be used for setting the predetermined degree of

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decorrelation of signals transmitted to different antennas);

- resulting random processes pass through a filter with the finite impulse response (FIR filter) in order to obtain samples with the correlation function of a given form.

According to [2], we will describe the cross-correlation function maximum using the following expression:

$$\rho = \exp\left(\frac{-2\pi\Delta^2(\tau V)^2}{\lambda^2}\right).$$

Here, Δ – effective width of antenna radiation pattern (ARP);

τV – space separation of receiving antennas in the lateral direction;

$\tau = \Delta\tau x$ (where $\Delta\tau = N_{\text{уср}}/f$ – sample spacing, x – number of samples);

$N_{\text{уср}}$ – number of averaged samples;

f – random process sampling rate;

V – velocity vector modulus;

λ – radiated signal wavelength.

A variation of the backscattering pattern (BSP) would result in recalculation of filter coefficients, which requires a certain digit capacity margin. Instead we propose a change in the sampling period.

For Δ equal to 5°, 10°, 15°, 20°, 30°, 40°, we select $N_{\text{уср}}$, equal to 512, 256, 171, 128, 85, 64, respectively. Values $N_{\text{уср}}$ are selected in such a manner so that the product of Δ multiplied by $N_{\text{уср}}$ is constant. The cross-correlation function takes the form shown in Fig. 1.

According to the data of Fig. 1, the cross-correlation function actually remains unchanged relative to the effective width of ARP. This allows to simulate a change of the type of underlying surface.

Based on the above, in order to obtain a random signal with given correlation properties, it is necessary to carry out the FIR filtering of a random normal process. For this purpose, we need to synthesize a discrete shaping filter that transforms the white noise into a correlated discrete random process with the given correlation and spectral characteristics [3].

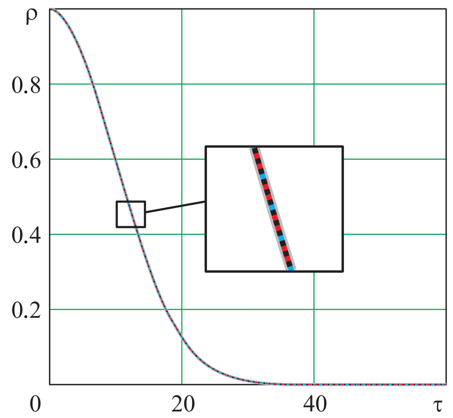

Fig. 1. Change of cross-correlation function depending on Δ and $N_{\text{уср}}$; ρ – correlation function

To determine weight coefficients of the shaping filter, we will use the spectral density function expansion into Fourier series. Let us calculate the spectral density for the determined correlation function using the following formula

$$G(\omega) = \int_{-\infty}^{+\infty} \rho(\tau) e^{-j\omega\tau} d\tau = \frac{\lambda}{\Delta V\sqrt{2}} \exp\left(-\frac{\omega^2\lambda^2}{8\pi\Delta^2 V^2}\right),$$

where ω – angular frequency.

We will determine the weight coefficients as Fourier coefficients through cosine-series expansion of the spectral density function of the process being simulated, with the function raised to the power of 0.5:

$$c_k = \frac{1}{\omega_c}\int_0^{\omega_c} \sqrt{G(\omega)} \cos\left(\frac{k\pi\omega}{\omega_c}\right) d\omega,$$

where $\omega_c = \pi/\Delta\tau$.

To simplify implementation of filtering on the simulator’s hardware level, we will write the weight coefficients in the following form:

$$c_k = \left[\frac{256\cdot 6c_k}{S_c} + 0.5\right]_{\text{ц.ч.}}$$

where k – coefficient index;

S_c – sum of weight coefficients of the shaping filter. Index ц.ч. means the integral part.

Fig. 2 shows the dependence of weight coefficients of the shaping filter on the number of averaged samples $N_{\text{уср}}$ (at $N_{\text{уср}} > 16$, the curve will asymptotically tend to zero).

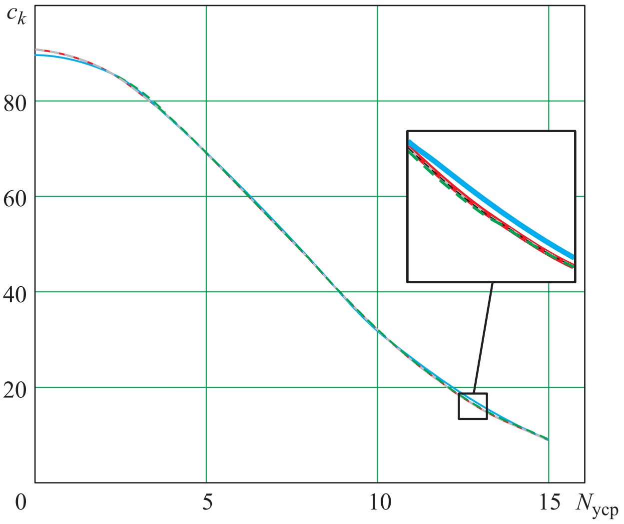

Fig. 2. Dependence of the shaping filter's weight coefficients c_k on the number of averaged samples $N_{\text{уср}}$

Actually, weight coefficients depend neither on ARP width values nor on the subsampling value (see Fig. 2).

To generate correlated samples, the simulator uses the 31st-order filter [4], so we calculate 16 weight coefficients. Coefficients $c_1, \ldots, c_{15}$ are symmetrical to coefficients $c_{16}, \ldots, c_{30}$.

The functional diagram of the simulator of correlated signals in the CRM receiving channels is shown in Fig. 3.

Random sequence generators (RSG) together with Gaussian signal converters (GSC) generate six normally distributed random processes. Correlated signal shapers (CSS) limit the spectrum width using the shaping filter, providing a given width of the cross-correlation function. Data is transmitted from the filter output to the cache memory where the digital delay line is implemented. Using the delay line helps set signal transport delays that correspond to the values of longitudinal component V_x and lateral component V_z of the velocity vector. Multiplying by signal process correlation coefficients and noise process decorrelation coefficients allows to form modulation laws, the cross-correlation functions of which will have the required maximum values. The resulting laws are applied for amplitude and phase modulation of signals transmitted to the CRM receiving channels, using controlled digital attenuators and phase shifters.

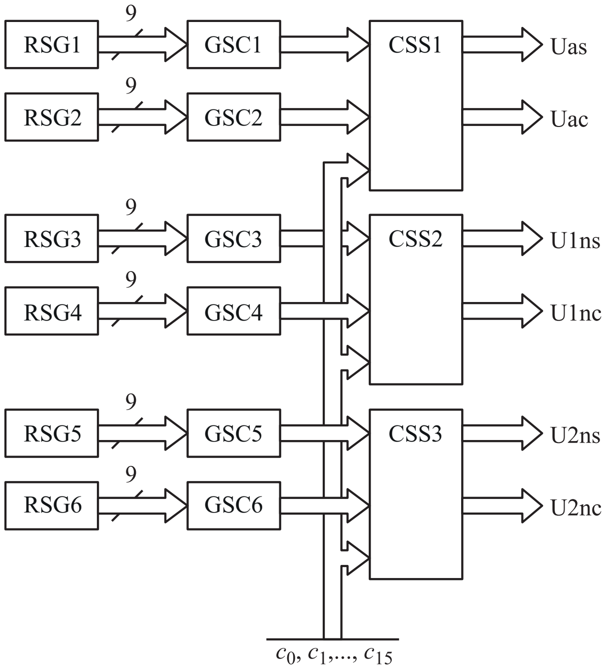

Fig. 3. Functional diagram of correlated signal simulator

Below we will describe the procedures needed to obtain three random signals to be used for signal modulation in three CRM receiving channels (see Fig. 3).

1. Formation of six uniform random processes using the multiplicative algorithm:

$$x_{i+1} = \text{remainder of division}\left[(4353x_i + 125),\ 2^{24}\right].$$

To optimise the digit capacity of the random number sequence considered above (range of 0…2^{24}), we will normalize it to the range of 0…2^9:

$$x_i' = \text{remainder of division}\left[(x_i/2^{12})_{\text{ц.ч.}},\ 2^9\right].$$

Fig. 4 shows samples of the process generated by a given algorithm, plus random process distribution.

2. Obtaining of random processes with the Gaussian distribution, based on uniform random processes. To form a random process with the normal law of distribution, we can use the central limit theorem of probabilities of identically distributed random variables: if each of K independent identically distributed random variables has mathematical expectation $m(x)$ and root-mean-square deviation $\sqrt{D(x)}$,

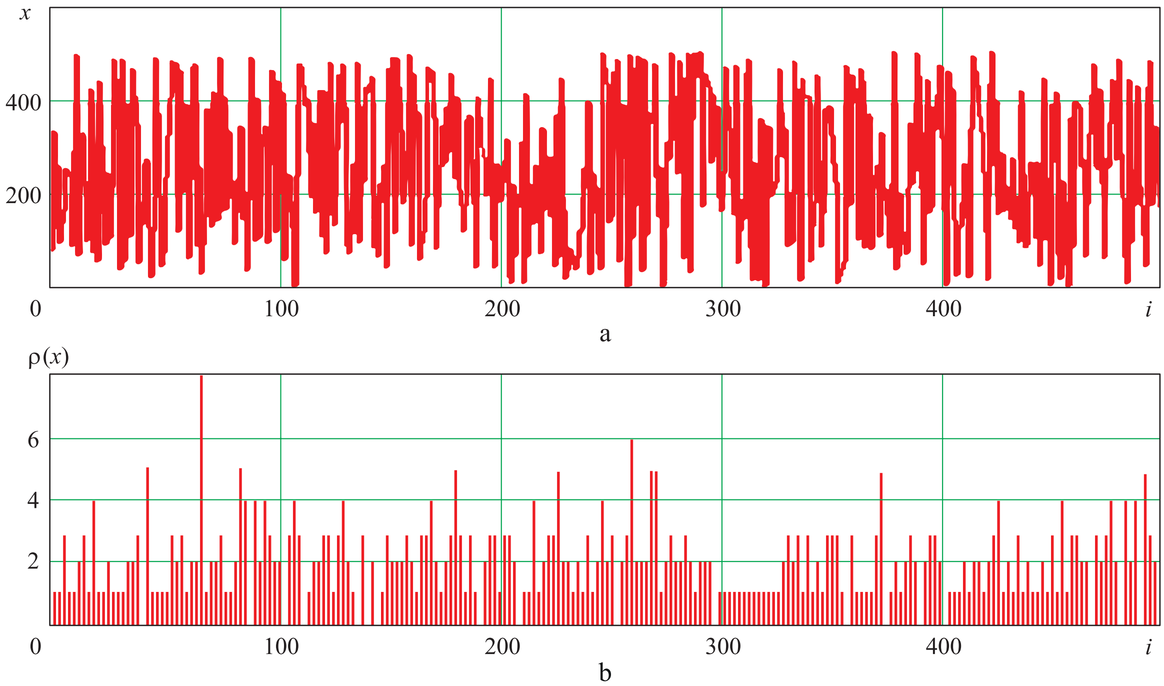

Fig. 4. Samples of uniform random process (a) and its distribution (b)

the sum $y_i = \sum_{i=1}^{K} x_i$ is asymptotically normal with mathematical expectation $m(y) = Km(x)$. Fig. 5 shows the diagram of the resulting random process and its distribution.

3. Formation of samples of correlated processes, using a shaping filter and calculated weight coefficients. For this purpose, we will use the shaping filter described above. The results are shown in Fig. 6.

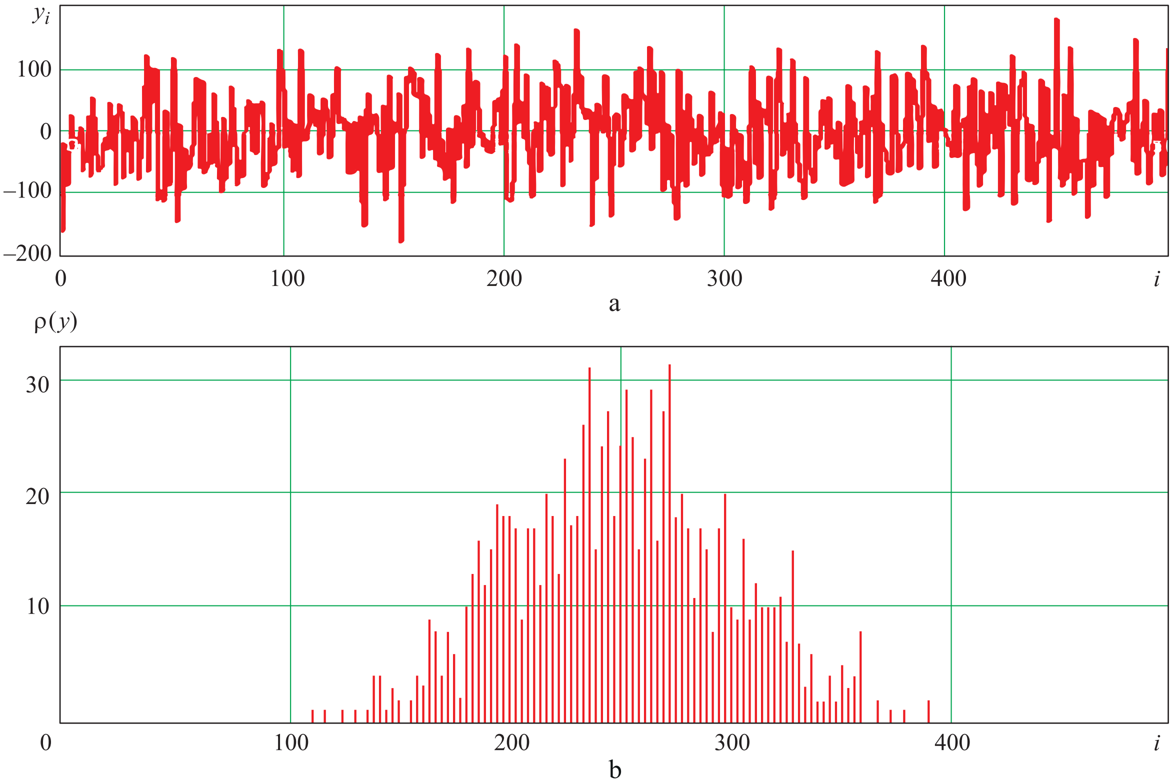

Fig. 5. Random process with Gaussian distribution (a) and distribution of random process (b)

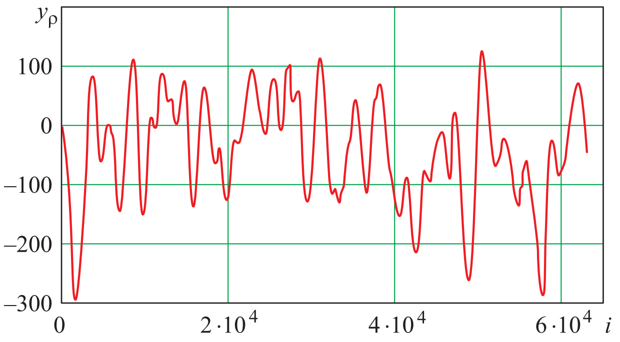

Fig. 6. Random process of a given correlation function

4. Formation of sample sequences with the set transport delays, using resulting correlated processes. To extract the components of three signals for the CRM receiving antennas from six resulting random processes *U1*, …, *U6*, we will use the following formulae:

- for the first antenna

$$U\sin_i = k_1 U_{1i} + \sqrt{1-k_1^2}\,U_{3i},$$

$$U\cos_i = k_1 U_{2i} + \sqrt{1-k_1^2}\,U_{4i};$$

- for the second antenna

$$U\sin_i = U_{1i+N1},$$

$$U\cos_i = U_{2i+N1};$$

- for the third antenna

$$U\sin_i = k_3 U_{1i+N1+N2} + \sqrt{1-k_3^2}\,U_{5i},$$

$$U\cos_i = k_3 U_{2i+N1+N2} + \sqrt{1-k_3^2}\,U_{6i},$$

where k_1, k_3 – signal decorrelation coefficients of the first and third antennas, respectively, relative to the second antenna;

N_1, N_2 – transport delays converted into samples.

Let us calculate coefficients k_1, k_3 using formulae [2]:

$$k_1 = \exp\left(-\frac{2\pi\Delta^2 X_0^2 \sin^2(\beta-\alpha)}{\lambda^2\cos^2(\beta)}\right);$$

$$k_3 = \exp\left(-\frac{2\pi\Delta^2 X_0^2 \sin^2(\beta+\alpha)}{\lambda^2\cos^2(\beta)}\right),$$

where X_0 – half of space separation of receiving antennas in the longitudinal direction;

β – drift angle;

α – angle characterising the antenna system.

Fig. 7 shows projections of positions of three CRM receiving antennas on the axis in the bound coordinate system.

Fig. 8 shows an example of implementation of modulating signal components.

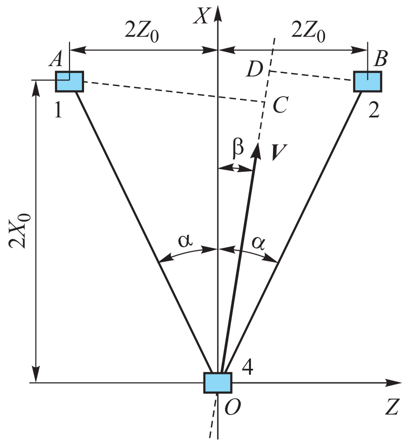

Fig. 7. Projections of positions of three CRM receiving antennas (designated by numbers):
A, *B* – centres of antennas;
Z_0 – half of space separation of receiving antennas in the lateral direction;
AC – first receiving antenna's normal to the ground speed vector

Thus, the developed correlated signal model for the CRM velocity simulator allows to simulate an echo signal when flying over the underlying surface of a given type, which makes it possible to measure lateral velocity component V_z both in terms of transport delays and the difference in cross-correlation function maxima.

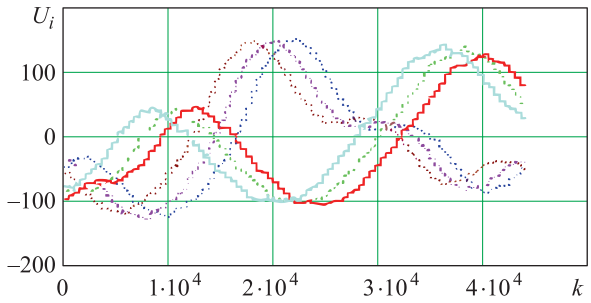

Fig. 8. Components of modulating signal;
U_i – modulating signal

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Модель коррелированных сигналов для имитатора скорости корреляционного радиолокационного измерителя

Одной из функций корреляционного радиолокационного измерителя (КРИ) высоты и составляющих вектора скорости является измерение составляющих вектора скорости, основанное на сравнении корреляционных характеристик сигналов, принятых на пространственно разнесенные антенны. Контрольно-проверочная аппаратура КРИ содержит упрощенный имитатор скорости, формирующий транспортные задержки сигналов в соответствии со значениями продольной и поперечной составляющих вектора скорости. Рассмотрена модель коррелированных сигналов, позволяющая имитировать отраженный сигнал, который дает возможность проводить измерение параметров, как по транспортным задержкам, так и по разности максимумов взаимно корреляционных функций (ВКФ).

Ключевые слова: корреляционный радиолокационный измеритель, имитатор скорости, модель коррелированных сигналов

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