Contemporary Engineering Sciences, Vol. 10, 2017, no. 1, 1 - 11
HIKARI Ltd, www.m-hikari.com
https://doi.org/10.12988/ces.2017.610164

Statistical Characteristics and Parameters of Spectrum of Doppler Signal Reflected from Extended Object

Vladimir Mikhaylovich Artyushenko

Technological University
Gagarin str., 42, Korolev, 141070, Russia

Vladimir Ivanovich Volovach

Volga Region State University of Service
Gagarin str., 4, Togliatti, 445017, Russia

Vyacheslav Grigorievich Kartashevskiy

Volga Region State University of Telecommunications and Informatics
Leo Tolstoy str., 23, Samara, 443010, Russia

Oleg Vladimirovich Osipov

Volga Region State University of Telecommunications and Informatics
Leo Tolstoy str., 23, Samara, 443010, Russia

Anatoly Ivanovich Tyazhev

Volga Region State University of Telecommunications and Informatics
Leo Tolstoy str., 23, Samara, 443010, Russia

Abstract

In the article we examine the results of theoretical and experimental studies of the statistical characteristics and of the parameters of the Doppler signal spectrum for different models of extended objects – transport means. Analysis and generalization of the obtained results was carried out based on a big selection of fragments of the Doppler signal spectrum that allows us to consider these results as statistically reliable. It is shown that acceleration motion of the extended object has the greatest influence on the width of the spectrum of the Doppler signal and, consequently, on the accuracy of the measurement of its speed of movement.

Keywords: Short Range Radar System, Extended Object, Spectrum of the Doppler Signal, Effective Width of Spectrum, Scattering Cross-Section, Speed of Motion, Acceleration of Motion

1. Introduction

Short-range radar systems (SRRS) are widely applied in various systems for measurement of movement parameters, protection systems of various objects, classification identification systems using the principle of short-range radar-location [1, 8, 12]. Consequently, they should also use other characteristics than those applied in the theory of long range radio systems.

Doing the theoretical justification and practical implementation of any devices belonging to the class of SRRS, for example, measuring device of motion parameters of various objects, you should consider a number of specific features for short range, such as the extended nature of the detected object, the comparability of geometric dimensions of the object with the distance to it, multipath nature of the reflection of signals from such objects, etc.

As a result, it is necessary to analyze the characteristics of reflection of the emitted signal, to define the width of spectrum of the Doppler signal (SDS), to select the method of definition and experimental determination of the scattering cross-section, and also to create on their basis mathematical models corresponding the real physical phenomena in SRRS taking into account the extended nature of the detected objects, constantly changing range, various laws of instantaneous detection probability, a priori uncertainty about the position of the object and its motion parameters [2, 11].

A priori knowledge of the statistical characteristics of signals and disturbing influences allows us to formulate more accurate mathematical models of the reflected signal as well as interferences influencing this signal and reasonable approach to the development of devices of SRRS. Previously the authors [3] have selected and justified models of disturbing influences on electronic detection devices (EDD) of high frequency type, which is a special case of SRRS taking into account multipath nature of the signals reflected from extended objects. It was noted that the probability density of the envelope of such a signal is well approximated by the Nakagami probability density distribution (PDD), and the PDD of the instantaneous values at specific values of the distribution parameters is clearly bimodal.

To create effective SRRD it is necessary to analyze the characteristics of the reflection of the probing signals from extended objects, to define the width of the

Doppler spectrum of the signal, to choose the definition method, to determine experimentally the effective surface (area) of the scattering, and to determine the statistical characteristics of signals received by SRRD. A priori knowledge of the statistical characteristics of signals and disturbing influences allows us to formulate more accurate mathematical models of the reflected signal and of the interference influencing this signal, similar to real physical phenomena in SRRD taking into account the extended nature of the detected objects, constantly changing range, different laws of instantaneous detection probability, a priori uncertainty about the position of the object and its motion parameters [4, 13, 14], and also to get a reasonable approach to the development of SRRD.

Characteristics of the received signal not only influence the range of SRRD, but also largely determine the number of other important indicators of the quality of their work, for example the probability of correct detection, the probability of skipping, the false alarm probability, the accuracy of measurement of speed and acceleration, the resolution, etc.

Note that here by received SRRD signals we will mean low-frequency (Doppler) signals generated at the output of the high-frequency part of SRRD (microwave sensor) after their conversion.

It should be noted that the analysis and generalization of the results of statistical processing was carried out by the numerous fragments of the received signal obtained during the detection of the extended object by SRRD (for each experiment transport means of the same model were used). Thus, the number of considered fragments from one model of each type of the extended object was 500...600. In this case the received signal of SRRD was recorded on more than fifty similar sets of radar devices of the microwave type.

To obtain the most complete statistical data the experimental studies were conducted under different climatic conditions: clear, sunny weather, dusk, rain, fog, frost and snow.

One of the objects of detection, changing motion parameters, ensuring traffic safety in the group, etc. SRRS are various transport means of railway transport and road transport, which by their structure can be attributed to the extended objects of complex shape. Particularly interesting is the study of the above mentioned transport means in connection with the special character of the reflections of the sounding signal coming from them. It is known [5] that a transport means as an object of detection is a complex spatially distributed radar target. Characteristics of the signal reflected from such a target, not only affect the range of SRRS, but also largely determine the number of other important indicators for such systems as: the accuracy of measurement of speed, resolution and other.

In general case, the signal reflected from objects of complex shape, contains two components: specular and diffuse. Specular reflection, i.e., the reflection in accordance with the laws of geometrical optics, is characteristic of smooth surfaces. Their characteristic size of roughness h is much less than the wavelength λ of the fluctuation generated by SRRD (i.e. $h \leq \lambda$) [6].

2. Spectrum of Doppler signal

As it is known [7], when measuring motion parameters of any extended object with radio methods the speed of its movement is determined by the Doppler frequency shift (DFS) of the signal:

$$f_d = \frac{\Omega_d}{2\pi} \approx -f_0 \frac{2V_r}{c} \cos\varphi = \frac{2V_r}{\lambda_0} \cos\varphi ,$$

where V_r is the radial velocity of movement of the detected extended object; λ_0 is the wavelength of the probing signal; φ is the angle between the direction of the axis of the main lobe of radiation pattern (RP) of the antenna and the direction of movement of the extended object.

Statistical properties of the received signal can be described [6] by the correlation function

$$B(t,t_1) = F\{x(t) \times x(t_1)\},$$

defined as the mathematical expectation of the product of samples of a random process, taken at time points t and t_1, or by the spectral density $S(\omega)$, defined as the Fourier transformation, of the correlation function, or by the spectral width of the received signal

$$\Delta f = 1/\tau_c , \qquad (1)$$

where τ_c is the correlation interval characterizing the rate of change of a random process in time [5].

A width of SDS can be estimated by the formula

$$\Delta F = F_d \cos 2\Delta\alpha ,$$

where $2\Delta\alpha$ is the angular size of the transport mean (in the horizontal plane).

The power of SDS can be determined from the expression:

$$P_d = P_{arp} S_\Delta k \sigma_{rr} \sin\varphi / 8\pi H^2 ,$$

where P_{arp} is the average radiated power; S_Δ is area of the aperture; k = 0,5…0,8 is the utilization factor of the antenna; σ_{rr} is the specific effective scattering surface (ESS) of extended object characterizing the reflective properties of the irradiated surface and is a function of the angle to the axis of the trajectory of an extended object φ; H is the distance (perpendicular) from the radar meter to the surface of the irradiated object.

The main factors determining the spectral and correlation characteristics of the received signals are the difference in velocities of the elemental reflectors located on the transport mean body and of SRRD, and changing the ESS of the elemental reflectors in time. The difference in velocities is caused by the large angular size of transport mean, exceeding in some cases the width of the radiation pattern (RP) of the SRRD antenna.

One of the most important statistical characteristics of the signal reflected from the extended object, affecting the accuracy of its speed measurement [7], is SDS [11]. The main parameters of the SDS are the average frequency of spectrum $f_{d.a}$, the envelope, the effective width Δf_{ew} and the power P_d [6].

The envelope and the effective width of the spectrum Δf_{ew} are determined by the resulting RP of the antennas in the plane of the angle φ. Also the effective width Δf_{ew}, as it was noted above [1], is affected by the correlation interval τ_c (1).

The effective width of the SDS is equal to its width at the level 0,5 by power and depends on the random fluctuations of the initial phase φ_r with the reflection $\partial\varphi_r/dt \neq 0$ [10], and on the differences of Doppler frequencies of the elemental reflectors within the RP of final width. The second factor is dominant.

For the case when the signal phase is changed according the polynomial law [15]

$$\Theta_{sd}(t) = \Omega_d t + \frac{\dot{\Omega}_d t^2}{2!} + \ldots, \qquad (2)$$

where the first summand Ω_d characterizes the speed of movement of the object, the second summand $\dot{\Omega}_d$ characterizes its acceleration.

The energy spectrum of signal (2) can be described by the expression [1]:

$$S(j\omega) = \int_{-T/2}^{T/2} S(t)\exp(-j\omega t)\,dt = \int_{-T/2}^{T/2} \cos\left[\Omega_d t + \frac{\dot{\Omega}_d t}{2!}\right]\exp(-j\omega t)\,dt\,, \qquad (3)$$

where $-T/2 < t < T/2$.

Using [9], we represent the expression (3) in the form

$$S(j\omega) = 0{,}5\sqrt{\frac{\pi}{\dot{\Omega}_d}}\exp\left[-j\frac{\left(\omega-\Omega_d^2\right)^2}{2\dot{\Omega}_d}\right]\int_{-X_1}^{X_2}\exp\left(-j\frac{\pi x^2}{2}\right)dx\,, \qquad (4)$$

where $X_1 = \left(\frac{\dot{\Omega}_d T}{2} + (\omega - \Omega_d)\right)\Big/\pi\dot{\Omega}_d$, $X_2 = \left(\frac{\dot{\Omega}_d T}{2} - (\omega - \Omega_d)\right)\Big/\pi\dot{\Omega}_d$.

In turn, the expression (4) can be represented as:

$$S(j\omega) = 0{,}5\sqrt{\frac{\pi}{\dot{\Omega}_d}}\exp\left[-j\frac{\left(\omega-\Omega_d^2\right)^2}{2\dot{\Omega}_d}\right]\left\{C(X_1) + jS(X_1) + C(X_2) + jS(X_2)\right\},$$

where $C(X) = \int_0^x \cos\left(\frac{\pi y^2}{2}\right)dy$ и $S(X) = \int_0^x \sin\left(\frac{\pi y^2}{2}\right)dy$ is the Fresnel integrals.

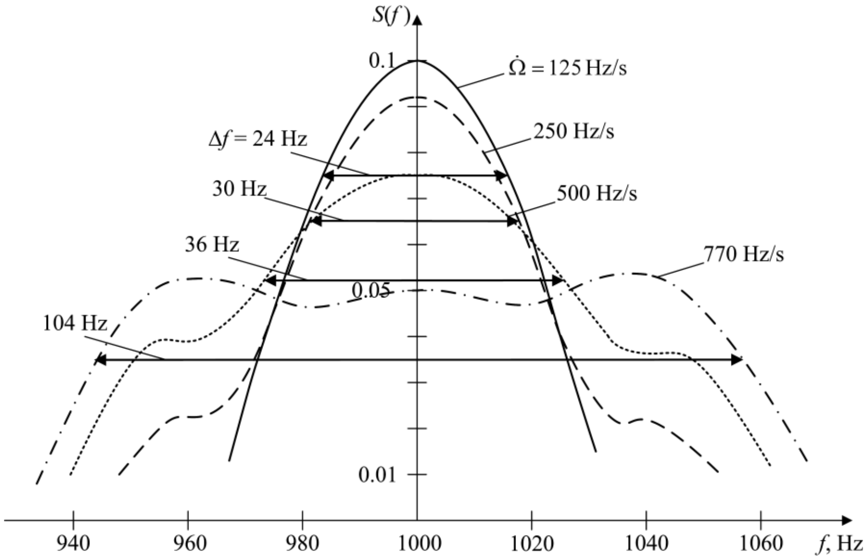
It is known that $C(-X) = -C(X)$ и $S(-X) = -S(X)$.

Previously [6] we obtained the expressions for the amplitude and phase spectra of the Doppler signal, respectively:

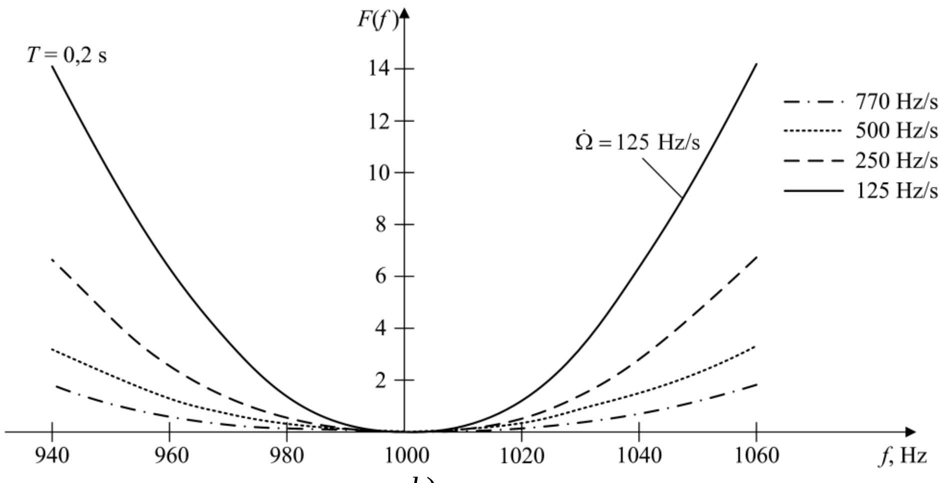
$$|S(\omega)| = 0{,}5\sqrt{\frac{\pi}{\dot{\Omega}_d}}\left\{[C(X_1)+C(X_2)]^2+[S(X_1)+S(X_2)]^2\right\}^{0{,}5}, \tag{5}$$

$$F(\omega) = \frac{(\omega-\Omega_d)^2}{2\Omega_d} - \operatorname{arctg}\left[\frac{S(X_1)+S(X_2)}{C(X_1)+C(X_2)}\right]. \tag{6}$$

The amplitude $S(f)$ and the phase $F(f)$ spectra calculated from the expressions (5) and (6) and built some of the values $\dot{\Omega}_d$ that characterize the magnitude of the acceleration of the object with the processing interval T = 0,2 c; $f = \omega/2\pi$, presented in Figure 1.



a)



b)

Figure 1. Amplitude *S*(*f*) (*a*) and phase *F*(*f*) (*b*) spectrum with *T* = 0,2 c

It should be noted that the amplitude spectrum of the signal oscillates around some constant value. The number of periods and the amplitude of the oscillations depends on the product $\dot{\Omega}_d T$ [5].

From the graphs it is seen that the width of the spectrum is influenced by two parameters $\dot{\Omega}_d$ and *T*. With a relatively large processing time, the influence of the parameter $\dot{\Omega}_d$ on the width of the SDS is predominant, which in this case has a trapezoidal shape with the oscillating amplitude.

With decreasing *T*, the expansion of the spectrum, caused by the value $\dot{\Omega}_d$, tends to zero, and the amplitude oscillations of the peak of the spectrum decrease, and its shape assumes a bell-shaped appearance. In this case, the decrease of the value *T* leads to expanding the spectrum and reducing its amplitude, and the peak of the curve of the dependency $S(f)$ becomes flat, and the edges assume a slightly sloping look.

3. Results of Doppler signal spectrum study

Next, let us proceed to study results of SDS parameters.

It should be noted that the methodology we use now was proposed by the authors before [1, 15]. Also earlier on the basis of the proposed method the authors experimentally determined the average values of scattering cross section (SCS) σ_{tm} transport means, the width of the SDS is ΔF_{tm} and root-mean-square deviation of the SCS on the example of different types of transport means. To summarize the obtained results it was interesting to carry out the research of more extended objects such as transport means of railway transport, as well as the study of the influence of acceleration of these objects on the parameters of the SDS.

An experimental study of the parameters of the SDS reflected from extended objects (train rolling-stock, single cars, in some cases for a shunting locomotive), was performed using microwave oscillations of serial radar speed gun with wavelength λ = 8 mm. Analysis and generalization of the study results of the parameters of the spectrum produced from the numerous fragments of the Doppler signal reflected from the transport mean of the same model. The number of the considered fragments from the transport means of each type was 380...400.

All of the spectra of the reflected signals can be divided into three groups. The first group will include the SDS under irradiation of the transport mean (train rolling-stock) at an angle close to zero when the transport mean is at a relatively large distance of about 50...60 m. For this case is characteristic the spectrum of the reflected signal, potentially providing a good accuracy of measurement of speed and, consequently, acceleration and high resolution.

The spectral width at the level of 0,707 is ΔF = 8…10 Hz.

The second group of spectra corresponds to positive angles of irradiation of the transport mean $\alpha_0 \geq 17^{o}$. In this case, the width of SDS increases significantly and is ΔF = 20...25 Hz, which corresponds to the location the transport mean at relatively small distances of about 10...20 m from the velocity meter. The angular dimensions of the transport mean often exceed the beam width of the antenna. Moving transport mean rapidly changes its angle, which is accompanied by rapid fluctuations of reflecting centers, which leads to the expansion of the SDS, the deterioration of the accuracy potential of the velocity meter and frequency resolution. In addition, this case is characterized by a sharp decrease in the SDS for some types of cars caused by the oblique fall of the ray on a smooth surface of the transport mean (mirror reflection), as well as some decrease of scatter of the values of SCS for different types of cars, due to the fact that the narrow beam of antenna irradiates only a part of the surface (projector mode).

The third group of spectra corresponds to the deceleration mode of the transport mean from the trigger point to the moment of release the car retarders. In this case the body of a railroad car as well as the velocity meter is exposed to strong vibration. In this case the spectrum of the reflected signal is expanded so that its width reaches ΔF = 30…40 Hz. Under these conditions the accuracy of the velocity measurement is the worst.

A significant expansion of the range is observed in Doppler signals reflected from shunting locomotives, because their body continuously vibrates from the running engine. Moreover, SDS does not only expand, but also has a «parasitic» harmonics, the amplitude of which is comparable with the spectrum of the main signal, which significantly affects the measurement accuracy, and can lead to errors in the velocity measurements.

The width of the spectrum of the Doppler signal at the level of 0,707 reflected from different models of wagons, are given in table 1, where $\delta_{ds} = \Delta F / F_{ds}$ is the relative measurement error of Doppler signal.

Table 1
The width of the spectra of the Doppler signals
reflected from various models of rail cars

The model of car	The width of the SDS signal ΔF, Hz (the level 0,707)					
	The first group		The second group		The third group	
	ΔF, Hz	δ_{ds}, %	ΔF, Hz	δ_{ds}, %	ΔF, Hz	δ_{ds}, %
11-066	8	1,0	25	1,8	38	3,5
12-515	12	1,25	23	1,6	34	2,8
15-1443	8	1,0	23	1,6	38	2,8
11-715	12	1,25	26	1,8	36	3,5
13-470	12	1,25	23	1,6	39	3,5
refrigerator	10	1,25	25	1,6	40	3,64
shunting locomotive	12	1,5	26	1,6	42	3,9

Each part of the table reflects the average over many realizations of the spectrum reflected from an uncoupling of the Doppler signal of moving in the area of the radar meter.

The results of processing of the experimental data show that when rotating wheels of the transport mean or its oscillating parts (for example, the rear and side doors, hatches, covers and accessories for fastening cargo) are irradiated, in the spectrum of the reflected signals appear additional components. Moreover, the frequencies of these components can be both above and below the frequency of the main signal, and their level is 10...40 dB below the main signal. It should be noted that the results obtained in this part of the study are absolutely identical to the earlier obtained results of study of similar parameters of SDS for road transport [3]. At low speeds of rolling of the transport mean the spectrum of the reflected signal is exposed to stronger «parasitic» effects than the spectrum of the signal reflected from the transport mean at a higher speed. This is because at low speeds of rolling of the transport mean the spectrum of the reflected signal falls within the frequency domain of additive noise, whose spectrum and the SDS «overlap». As a result of this not only the expansion of ΔF can occur, but its «splitting» as well, which greatly reduces possibility of accurate measurement of the Doppler frequency signal. As a result of experimental studies it has been shown that the transport mean movement acceleration has the greatest influence on the width of the SDS and, consequently, on the accuracy of speed measurement of the extended object movement (railway cars, transport means in general). Moreover, the bigger is its absolute value, the wider is the energy spectrum of the reflected signal, which is fully consistent with the theoretical analysis.

4. Conclusion

Considering a good compliance between theoretical and experimental results we can draw the following conclusions. The average value of the acceleration of railway cars rolling into brake position is within (+0,45)…(+0,55) м/с^2. At the time of braking, the acceleration is in the range of (–1,9)…(–2,1) м/с^2; respectively, in the output of the moderator it is(–0,05)…(+0,05) м/с^2. It should be noted that while technically implementing the tracking velocity meter for increasing accuracy of measurement of the average frequency of spectrum of the reflected signal, the time constant of the measurement must be chosen from the condition of minimum width of the Doppler reflected signal at the maximum possible acceleration value of the transport mean, taking into account the required processing speed of the meter in receiving and issuing information about velocity of the transport mean movement. As can be seen from the presented results, the time constant of the measurement must be within 80...120 ms.

References

[1] V. M. Artyushenko, *Research and Development of the Motion Parameters Radar Meter for Extended Objects*, Finance and Technology Academy, Moscow, 2013.

[2] V. M. Artyushenko and V. I. Volovach, Measurement Error Estimation of Motion Variables for Extended Objects under Changing Range Conditions, *Radioelectronics and Communications Systems*, **58** (2015), no. 1, 17 - 27. https://doi.org/10.3103/s0735272715010033

[3] V. M. Artyushenko and V. I. Volovach, Statistical Characteristics of Envelope Outliers Duration of non-Gaussian Information Processes, *Proceedings of IEEE East-West Design & Test Symposium (EWDTS'2013)*, 137 - 140. https://doi.org/10.1109/ewdts.2013.6673139

[4] V. M. Artyushenko and V. I. Volovach, Analysis of influence of uncorrelated additive non-Gaussian noise on accuracy of motion parameters measurement in short-range radio systems, *Proceedings of IEEE International Siberian Conference on Control and Communications (SIBCON-2015)*, 7147279. https://doi.org/10.1109/sibcon.2015.7147279

[5] V. M. Artyushenko and V. I. Volovach, Analysis of the spectrum parameters of a signal reflected from an extended object, *News of Higher Educational Institutions. Instrumentation*, **57** (2012), no. 9, 62 - 67.

[6] V. M. Artyushenko and V. I. Volovach, The study of spectrum of Doppler signal reflected from moving of extended object, *Successes of Modern Radio Electronics*, (2015), no. 11, 58 - 66.

[7] V. M. Artyushenko and V. I. Volovach, Threshold method of measurement of extended objects speed of radio engineering devices of short-range detection, *Proceedings of IEEE East-West Design & Test Symposium (EWDTS'2014)*, 220 - 223. https://doi.org/10.1109/ewdts.2014.7027078

[8] G. L. Charvat, *Small and Short-Range Radar Systems*, CRC Press, 2014.

[9] Ch. Cook, M. Bernfeld, *Radar Signals*, Sovetskoe radio, Moscow, 1971.

[10] A. G. Flerov and V. T. Timofeev, *The Doppler Device and Navigation System*, Transport, Moscow, 1987.

[11] L. Hammarstrand, L. Svensson, F. Sandblom and J. Sorstedt, Extended object tracking using a radar resolution mode, *IEEE Transactions on Aerospace and Electronic Systems*, **48** (2012), no. 3, 2371 - 2386. https://doi.org/10.1109/taes.2012.6237597

[12] I. V. Komarov, S. M. Smolskiy, *Fundamentals of Short-Range FM Radar*, Artech House, Norwood, 2003.

[13] N. Lu and B. Eisenstein, Detection of Weak Signals in non-Gaussian Noise, *IEEE Transactions on Information Theory*, **27** (1981), no. 6, 755 - 771. https://doi.org/10.1109/tit.1981.1056414

[14] J. J. Sheehy, Optimum Detection of Signals in non-Gaussian Noise, *The Journal of the Acoustical Society of America*, **63** (1978), no. 1, 81 - 90. https://doi.org/10.1121/1.381699

[15] G. I. Tuzov, *Allocation and Information Processing in Doppler Systems*, Sovetskoe radio, Moscow, 1977.

Received: October 20, 2016; Published: December 16, 2016