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FREQUENCY SELECTION OF HIGH-SPEED GROUP TARGETS IN THE CASE OF ACCUMULATION OF ECHO SIGNALS

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Using a harmonic continuous signal (wavelength 3 cm) as an example we considered consistency of traditional procedures of the Doppler selection under conditions of Doppler accumulation of reflected signals (several tens of milliseconds) and alternative approaches making it possible more effectively to solve the problem of frequency resolution of group targets.

One trend in the development of modern radiolocation is precision accounting in algorithms for signal processing of those factors, which in the classical theory were ignored or were treated in a simplified way. Among the examples of the success of such an approach one may point to increased accuracy of position finding based on accounting nonidentities of directivity characteristics of partial channels of antenna arrays [1]. The objective of the current article is the analysis of possibilities of highly precise spectral selection of group targets' elements in the case of prolonged accumulation of echo signals within the framework of traditional and new approaches to the realization of measuring procedures.

As is known, owing to small intervals between the elements of group targets, their resolution in terms of angular coordinates even within the framework of the super-Rayleigh approach is an extremely complex problem. This is the reason why a number of foreign projects prefer preliminary frequency discrimination ensuring the so-called "Doppler narrowing" of beams in the directivity pattern of the radar antenna system [2]. However, insignificance of speed differences between targets in dense group orders requires substantial time expenditure for realization of such an idea.

To a certain measure the performance of frequency resolution may be increased taking into account that owing to spatial spacing of the sources (even with identical speeds and directions of their movement) projections of the speed vectors on the "radar–target" sighting line have a different value. However, as our calculations showed, given small angles of the site and large distances from the radar these differences are infinitesimally small. Although in cases when with large increases differences in radial speeds become noticeable, highly-precise frequency selection is hindered by frequency deviation caused by the rotation of the sighting line of objects of location during accumulation time. Depending on its duration and target speed such deviation may account for 80% and more of Doppler frequency spacing.

For a detailed investigation of spectral distortions emerging when accumulating echo signals of group targets within several tens of milliseconds we conducted a mathematical simulation. In this case continuous harmonic oscillation of the form

$$u(t) = a \cdot \cos(\omega_0 t + \varphi_0), \qquad (1)$$

was considered as sounding. In the above expression a is the amplitude of the sounding signal, ω_0 is the radial frequency of the carrier frequency, φ_0 is its initial phase.

The motion of targets was assumed to be uniform, straight with horizontal orientation of the speed vector and its alignment with the vertical plane passing through the "radar–target" conventional line. In addition, the sources of reflected signals were assumed to be point-like, while amplitudes of their signals equal to the amplitude of the sounding one and identical for all targets. Such a hypothesis is not without foundation since in the problem discussed similar close-lying objects have practically equal effective target area. The value of losses, however, during reflection just as rotation of the initial phase in the given case is not important.

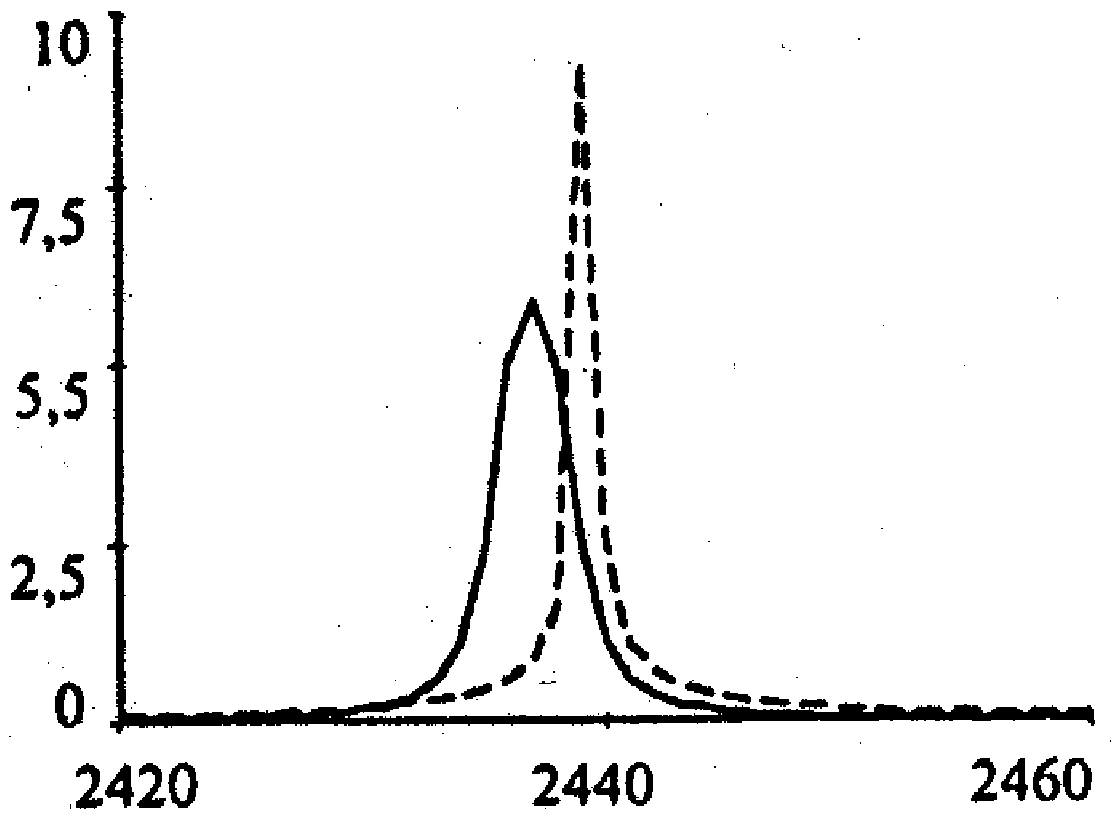

Fig. 1

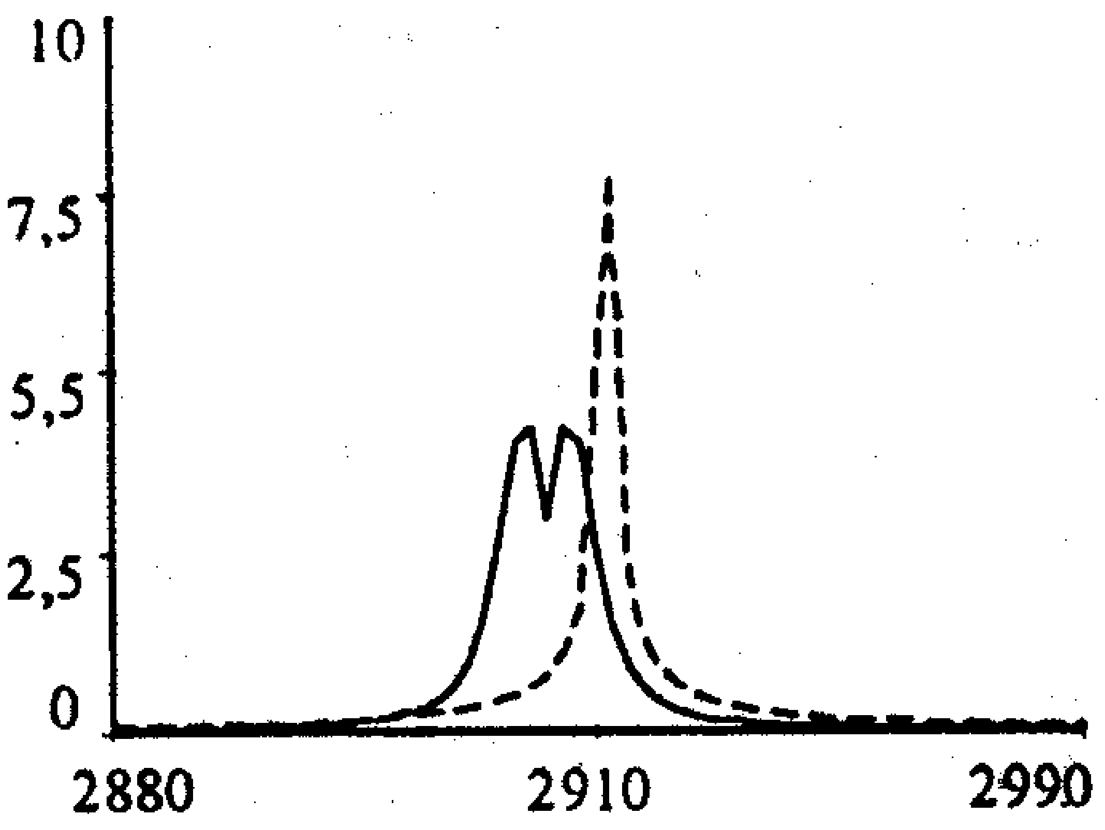

Fig. 2

To achieve the adequacy of the signal $U_{s\,\mathrm{ref}}$ model each sth's ADC sample was assigned according to the current value of the inclined range of the target R_s, i.e.

$$U_{s\,\mathrm{ref}} = a_{\mathrm{ref}} \cdot \cos\left(\omega\, \Delta t\,(s-1) - \omega_0 \frac{2R_s}{c} + \varphi_{\mathrm{ref}}\right), \tag{2}$$

where $R_s = \sqrt{R_0^2 - 2\,V R_0\,(s-1)\,\Delta t \cos\varepsilon_0 + V^2\,\Delta t^2\,(s-1)^2}$, R_0 is the value of the target's inclined range at the instant of accumulation beginning, V is the absolute value of its speed vector, ε_0 is the angle of the target's position at the instant of accumulating echo signals, a_{ref}, φ_{ref} are the amplitude and phase of the reflected signal, Δt is ADC digitization period, ω is the radial frequency of signal filling at the ADC output, ω_0 is the radial frequency of the sounding signal carrier frequency, c is the speed of light.

In the case of a pulse signal it is advisable to replace the subscript "s" in R_s in (2) by the number of the sounding period and assume that within echo signal duration the target position in space does not have time to vary. Within the framework of such assumption instead of ADC samples it is possible to use the results of their partial summation fulfilled according to the methods considered in [3].

Figures 1 and 2 in the form of a solid line show the result of the fast Fourier transform (FFT) for 40% of the samples of voltages obtained within the interval of 60 and 80 ms, respectively, from a single source of the continuous signal having the wavelength of 3 cm, target height H_{t1} = 5,000 m, range D_{t1} = 5,000 m, and speed V = 500 m/s. The numbers of frequency filters are laid off on the horizontal axis, while FFT response amplitudes on the vertical axis. For comparison the dotted line shows the result of a similar processing applicable to the ideal situation of investigating a stationary harmonic oscillator located at the initial point of the first target's trajectory. This is the result, which, as a rule, is relied on, ignoring the rotation of the sighting line.

As a result of simulation for conditions specified the possibility was confirmed of using algorithms of spectral estimation oriented to the harmonic signal, if the accumulation time constitutes 40 ms. However, in this case the estimates of the frequency of the source in motion acquire an expressed shift.

When the accumulation interval is increased to 60 ms (Fig. 1) the harmonic model loses its independence. Nevertheless, the single-mode nature of the envelope of the localized spectral section corresponding to the signal of the reflector in motion makes it possible to conduct sufficiently accurate selection of the energy center of the signal response using the method of maximum probability. The corresponding processing algorithm consists of iteration estimation of the frequency of the real echo signal ω by maximization of the function

$$F_{\mathrm{m}} = a^c \sum_{s=1}^{S} U_s \cos p_s - a^s \sum_{s=1}^{S} U_s \sin p_s = \max, \tag{3}$$

where

$$a^c = \left[\sum_{s=1}^{S} \sin^2 p_s\, D_1 - 0.5 \cdot \sum_{s=1}^{S} \sin 2\,p_s\, D_2\right] \cdot \widetilde{D}^{-1}, \quad D_1 = \sum_{s=1}^{S} U_s \cos p_s,$$

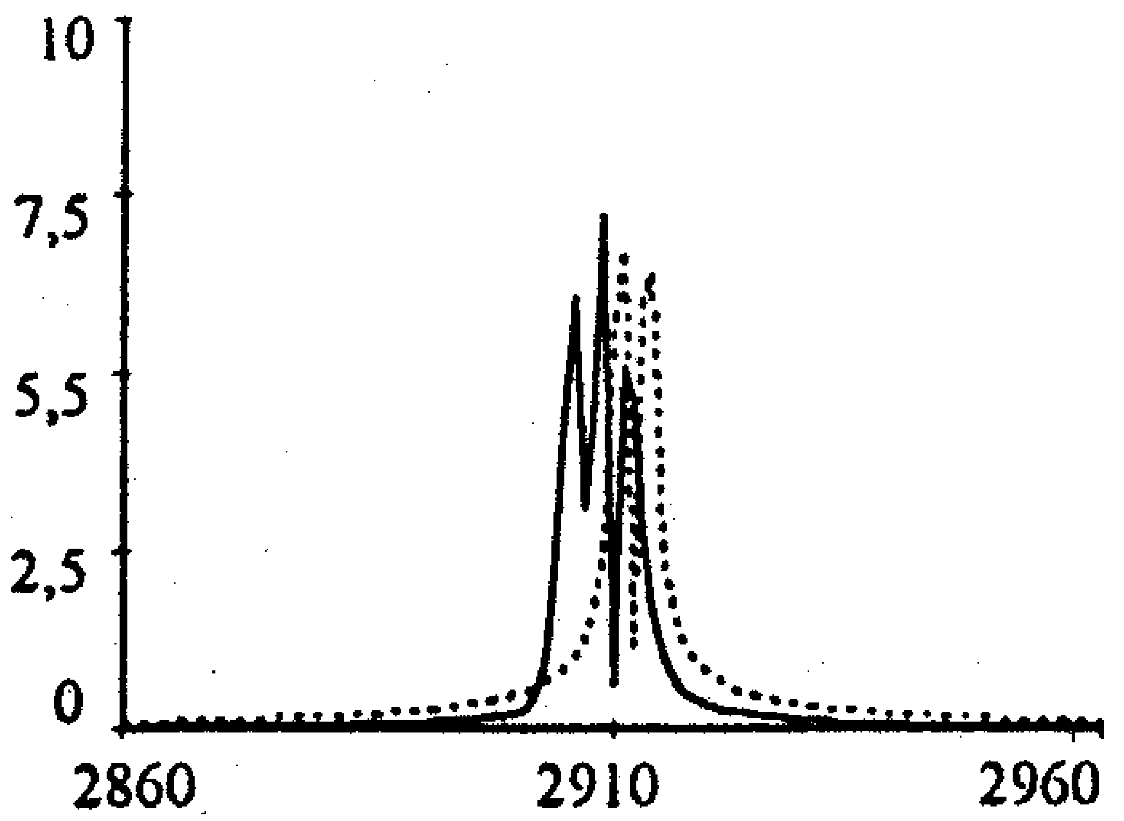

Fig. 3

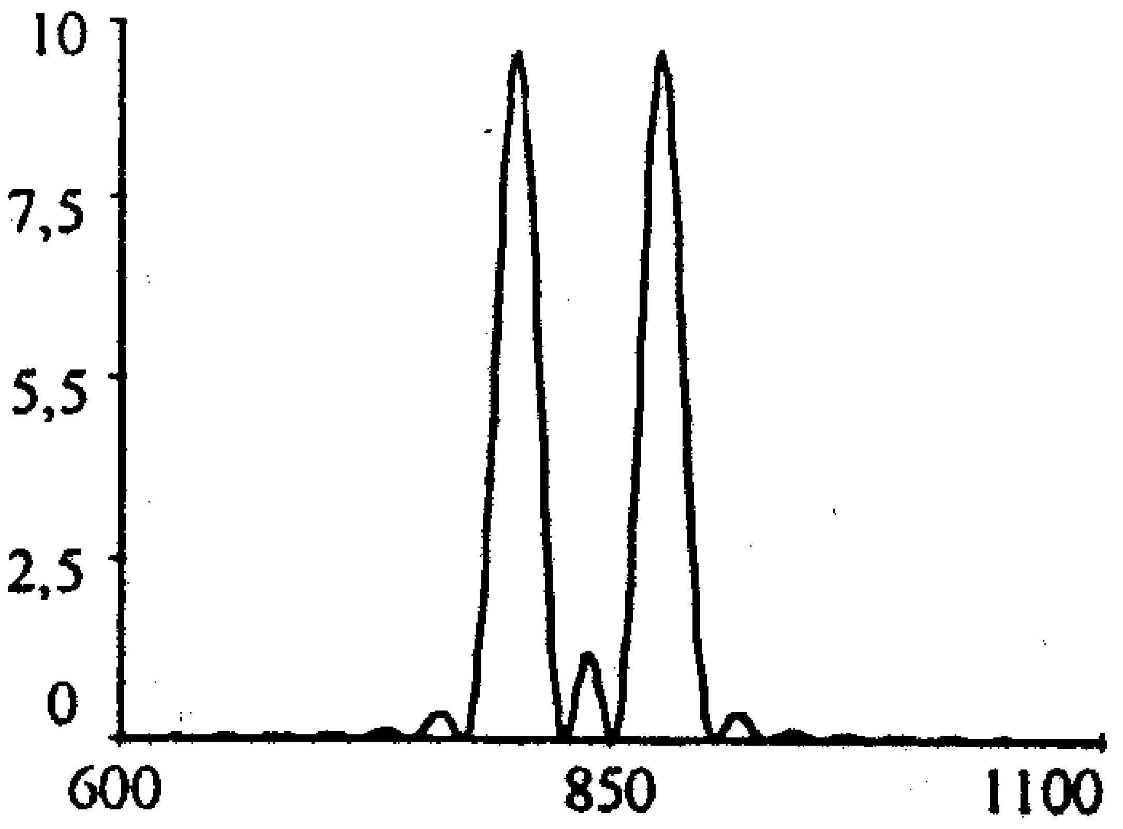

Fig. 4

$$a^s = \left[-\sum_{s=1}^{S} \cos^2 p_s D_2 + 0.5 \cdot \sum_{s=1}^{S} \sin 2 p_s D_2 \right] \cdot \tilde{D}^{-1}, \quad D_2 = \sum_{s=1}^{S} U_s \sin p_s,$$

$$\tilde{D} = \begin{vmatrix} \sum_{s=1}^{S} \cos^2 p_s & -0.5 \cdot \sum_{s=1}^{S} \sin 2 p_s \\ -0.5 \cdot \sum_{s=1}^{S} \sin 2 p_s & \sum_{s=1}^{S} \sin^2 p_s \end{vmatrix}, \quad p_s = \omega \cdot \Delta t\,(s-1).$$

As the accumulation interval increases further, up to 80 ms (Fig. 2) the envelope of the signal spectral response becomes multi-mode and the problem of accurate estimation of frequency without taking into account rotation of the sighting line loses sense. In this case for successful solution of the measuring problem in procedure (3) one has to take into consideration the law of the evolution of the Doppler frequency increment. In the simplified version of the signal model considered for this goal it is enough to replace the argument $p_s = \omega \cdot \Delta t\,(s-1)$ by substitution of $p_s = \omega\,\Delta t\,(s-1) - \omega_0 \frac{2R_s}{c}$. As a result of frequency selection one will have to do an exhaustive search for all unknowns whose role is played by the values R_0, V, ε_0.

In the case of successful selection of the evolution law of the multiplier R_s such an approach makes it possible to reduce the extension of the signal spectrum (Fig. 1). In the situation involving one target it makes sense to stop the process of exhaustive search for unknown parameters in (3) upon the attainment of the width of the localized signal section of the prescribed minimum. The simulation results obtained under conditions cited above corroborated convergence of the estimation iteration procedure.

In the ideal case, when the distance of the sources is known, processing (3), taking into account frequency deviation, makes it possible under conditions of prolonged accumulation to discernibly improve the visually perceptible spectral resolution. As confirmation of the above we will turn to the simulation results of the two-signal reception situation presented in Figs. 3 and 4. The first of them (Fig. 3) in the solid line shows the result of a 4,096-dot FFT of 80-millisecond sampling of a noiseless mixture of signals of two sources (the parameters of the first correspond to the data for Figs. 1, 2, while those of the second one: H_{t2} = 4,995 m, D_{t2} = 5,010 m, V = 500 m/s).

One can clearly see that frequency responses of the signals merged into a solid three-mode segment. Their visual resolution in the Rayleigh sense does not appear to be possible although the spacing at the Doppler frequency (without taking into account deviation) in fact exceeds the filter width (the dotted line shows the result which will take place when the sources move along the sighting line).

Figure 4 shows the result of fulfillment applicable to the situation under consideration of one-target measuring procedure (3) allowing for $p_s = \omega\,\Delta t\,(s-1) - \omega_0 \frac{2R_s}{c}$. In this case the exhaustive search was carried out at the unknown flight speed V while as the values R_0, ε_0 we used their magnitudes for the first target at the accumulation instant. The result of such simplification of the shift of the signal frequency estimate of the second source (the magnitudes of the target speed are shown along the horizontal axis).

It should be noted that the shift of the resultant estimates might be asymptotically reduced to zero based on the approach taking into account the number of echo signals and reducing in the given case to the use of the two-signal measuring procedure

$$F_m = \sum_{m=1}^{2} a_m^c \sum_{s=1}^{S} U_s \cos p_{ms} - \sum_{m=1}^{2} a_m^s \sum_{s=1}^{S} U_s \sin p_{ms} = \max, \qquad (4)$$

where

$$a_m^c = D_m^c / D; \quad a_m^s = D_m^s / D,$$

$$D = \begin{vmatrix} B_{11} & C_{12} \\ C_{21} & B_{22} \end{vmatrix}, \quad B_{nn} = \begin{bmatrix} \sum_{s=1}^{S} \cos^2 p_{ns} & -0.5 \cdot \sum_{s=1}^{S} \sin 2 p_{ns} \\ -0.5 \cdot \sum_{s=1}^{S} \sin 2 p_{ns} & \sum_{s=1}^{S} \sin^2 p_{ns} \end{bmatrix},$$

$$C_{nm} = \begin{bmatrix} \sum_{s=1}^{S} \cos p_{ns} \cos p_{ms} & -\sum_{s=1}^{S} \cos p_{ns} \sin p_{ms} \\ -\sum_{s=1}^{S} \cos p_{ms} \sin p_{ns} & \sum_{s=1}^{S} \sin p_{ns} \sin p_{ms} \end{bmatrix}, \quad C_{nm} = C_{mn}^T, \quad p_{ns} = \omega_n \Delta t (s-1) - \omega_0 \cdot \frac{2 R_s}{c},$$

with the determinants D_m^c and D_m^s obtained from the determinant D by the replacement of the corresponding mth even (for D_m^c) or odd (for D_m^s) column by the vector of free terms $\{W_1, W_2\}^T$ in which

$$W_m = \left[-\sum_{s=1}^{S} U_s \cos p_{ms} \quad \sum_{s=1}^{S} U_s \sin p_{ms} \right]^T.$$

The absence of a priori information on the number of sources inevitably implies overlapping the problem solution on frequency selection with the verification of a package of possible hypotheses relative to the qualitative composition of group targets. In the given approach for this it is enough to use the search for maximorum maximum on the ensemble of responses of the whole admissible set of functions of type (3) and (4) with the subsequent choice as the finite result of the measurement of that set of estimates which corresponds to the greatest magnitude of iteration functions.

Thus, estimation procedures (3) and (4) synthesized based on the method of maximum probability given the validity of the assumptions mentioned make it possible to solve the problem of frequency selection of echo signals in the case of large accumulation intervals. However, as the number of sources increases and taking into account three-dimensional characteristics of their motion in space the proposed approach for unshifted estimation of frequency becomes quite cumbersome. This reduces the effectiveness of frequency resolution and assigns to range measurement the role of the preferred means of separate measurement of parameters for each object of a group target.

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