# The Principle Probabilities of Space-Distance Resolution for a Monostatic Radar and Realization in Cylindrical Array

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***Abstract*—**In conjunction with the problem of the target selection on a clutter background, the analysis of the scanning rate influence on the spatial-temporal signal structure, the generalized multivariate correlation function and the quality of the resolution with the increase pulse repetition frequency is made. The possibility of the object space-distance resolution, which is conditioned by the range-to-angle conversion with an increased scanning rate, is substantiated. The calculations for the real cylindrical array at high scanning rate are presented. The high scanning rate let to get the signal to noise improvement of the order of 10 dB for the space-time signal processing.

***Keywords*—**Antenna pattern, array, signal processing, spatial resolution.

## I. Introduction

THIS paper deals with the problem of the radar target detection on a clutter background. The use of continuous or quasi-continuous radar radiation is an effective way to improve moving target extraction from clutter [1], i.e., time (Doppler) signal processing. However, here an ability to receive weak useful signals from maximally distant targets is hampered by intense clutter originating at a close range because signals and clutter, reflected at different distances, are received at the same time with continuous or quasi-continuous radiation. So, far-range target echoes are received on a close clutter background. In this case, it would be tempting to perform a clutter suppression by a space processing of signals (by a receiving antenna). This suppression is impossible without a spatial resolution of radar echoes originating at different distances. The detailed resolution analysis [1] does not mention using of similar resolution in monostatic systems and suggests the increase of the antenna aperture and the narrowing of the antenna pattern (AP) as the only way of the space suppression of clutter. However, these recipes ignore scanning. Some results of the development of the mentioned theory with the scanning are presented below. In particular, capabilities of a radar echo resolution and selection of continuous or quasi-continuous signals on a clutter background are described.

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## II. Analysis of Spatial Resolution

This paper aims at estimation of the space signal selection on a clutter background with equality of their angular coordinate.

The efficiency of a space processing of signals on a clutter background in the case of the cylindrical array use with high scanning rate in the azimuth plane is proved in our work [2].

Only AP in the scanning plane (in the azimuth plane) has the substantial consequence for the space clutter suppression with high scanning rate. For a rectangular plane array, such AP is determined by horizontal linear array characteristics (i.e., subarray of plane array), and for a cylindrical array, it is determined by ring subarray characteristics [2]-[4]. Therefore we consider the horizontal ring array as the antenna system model i.e., the antenna system, rotating around its center at a fixed rate $\Omega$ rad/s in the scanning plane $(\alpha, R)$, where $\alpha$ is the angular coordinate (azimuth), $R$ is the radial coordinate (range) measured from the center of the rotation. The zeros of the time $t$ and angle $\alpha$ are taken so that the value $\Omega t$ of this angle defines the normal to the receiving antenna. We will denote also: $\lambda$ is the operating wavelength, $v(t)$ is the normalized complex envelope of the probe signal, $G_{b0}(\varepsilon)$ is the normalized transmitting AP with the direction of the principal maximum $\varepsilon = \varepsilon_{b0}$, where $\varepsilon = \alpha - \Omega t$ is the angle measured from the normal to the receiving antenna in the scanning plane. Let us assume that $x$ is the coordinate along the receiving antenna with the aperture dimension $\Pi$ and the value $x = 0$ corresponds to the antenna center.

The approach [4] allows us to define a space-time moving target echo signal (the complex envelope value of the field intensity at the point $x$ and at a time $t$):

$$y_x(t) = \mu' w(x)(R + \dot{R}t)^{-1} R_x^{-1} v\left(t - \frac{R + \dot{R}t + R_x}{c}\right) G_{b0}\left\{(\alpha + \dot{\alpha}t) - \right.$$
$$\left. -\Omega\left(t - \frac{R + \dot{R}t + R_x}{c}\right)\right\} \exp\left\{-j2\pi \frac{R + \dot{R}t + R_x}{\lambda}\right\} \approx$$
$$\approx \mu'' R^{-2} w(x) \exp(j\omega t) v(t - t_R) G_{b0}\left\{\alpha - \Omega(t - t_R)\right\} \exp\left\{j2\pi \frac{x}{\lambda}(\alpha - \Omega t)\right\}, \quad (1)$$

where $\alpha + \dot{\alpha}t$ and $R + \dot{R}t$ are variable coordinates of the target,

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$\dot{\alpha}$ and $\dot{R}$ are velocities of coordinate modifications, $R_x$ is the distance between the target and an aperture point $x$, $c$ is the electromagnetic wave velocity, $j=(-1)^{1/2}$, $\pi = 3.14 ...$, $\omega$=-4$\pi\dot{R}/\lambda$ is the Doppler frequency shift, $\mu'$ and $\mu''$ are complex constants,

$$w(x) = \begin{cases} 1 \text{ for } |x| \le \Pi/2, \\ 0 \text{ for } |x| > \Pi/2, \end{cases} \quad (2)$$

$$t_R = 2R/c.$$

Equation (1) reflects the signal attenuation with its propagation, the signal propagation time delay, the rotation of the transmitting AP and the receiving antenna aperture between moments of the transmission and the reception of the signal. In other words (1) is obtained with the modelling of the transmitting antenna as the rotating AP, with the modelling of the receiving antenna as the rotating aperture and this formula corresponds to the signal transmitted from the antenna phase center, located at the rotation center, and received at the point $x$ in the aperture.

The magnitude of the last part of (1) is maximized at the time

$$t = t_{\max} \approx t_R + \frac{\alpha - \varepsilon_{b0}}{\Omega}. \quad (3)$$

The last exponential factor in (1) with consideration of (2) and (3) shows that scanning $(\Omega \ne 0)$ provides the range-to-angle conversion. This is a transformation of the target range differences into space differences of echo signals. These space differences can arise without scanning only as a consequence of angle coordinate differences of targets. The fact of existence of such conversion is not widely known. As a result, the possibility of space (on the basis of the aperture phase-distribution differences) resolution of echoes, originating at different distances, arises. It should be noted that analysis of the electronic scanning and of the space-time signal on the outputs of controlled phase-shifters of a receiving array will lead to similar results.

We will find the criterion for the space-distance resolution (the generalized Woodward constant [1]):

$$\delta = \int_{-\infty}^{+\infty} |(\chi_0(0,\ t'_R,\ 0)|^2 dt'_R, \quad (4)$$

where the section of a domain with that boundary, which in the 4-dimensional hyperspace is modulus squared of normalized generalized space-time ambiguity function, is integrated

$$\chi_0(\alpha',\ t'_R,\ \omega') = \frac{\chi(\alpha',\ t'_R,\ \omega')}{\chi(0,\ 0,\ 0)}, \quad (5)$$

$$\chi(\alpha',\ t'_R,\ \omega') = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} y_x^*(t+t') y_x^0(t) dx\, dt, \quad (6)$$

the symbol * denotes the complex conjugate, a standard signal is

$$y_x^0(t) = y_x(t)\Big|_{\text{for } \alpha=\alpha^0,\ R=R^0,\ \omega=\omega^0}, \quad (7)$$

$$\alpha' = \alpha - \alpha^0,\ t'_R = t_R - t_R^0,\ \omega' = \omega - \omega^0,\ t_R^0 = 2R^0/c. \quad (8)$$

Let us assume that the chosen value $t'$ provides the time combination of factors (signals) in the integral (6). Then for $\alpha' = 0$ and $\omega' = 0$ only the above-mentioned range-to-angle conversion allows the signal resolution. With these assumptions, (1)-(8) result in

$$\delta = \lambda \Pi^{-1} \Omega^{-1} \approx \theta_w \Omega^{-1}, \quad (9)$$

where $\theta_w \approx \lambda \Pi^{-1}$ is the width of the receiving AP in the scanning plane.

According to the obtained formula (9) the space-distance resolution is improved not only with the antenna aperture increase or with the AP narrowing (this is accustomed for a spatial resolution) but also with the high scanning rate. Notice that the value $\delta$ is measured as a signal delay time. The associated resolution, measured as a range, is

$$\delta_R = c\delta/2 = c\lambda/(2\Pi\Omega) \approx c\theta_w/(2\Omega).$$

## III. Space Attenuation of Clutter

We consider the continuous or quasi-continuous radar radiation and the problem of the selection of the signal on a clutter background (see Section I). Moreover, according to the peculiarity of the problem, the signal and a clutter are reflected at different distances. Namely, the signal originates at a range $R_s$, and clutter originates at a range $R << R_s$. Consequently, in our case

$$\delta_R \le R_s \text{ or } \delta \le t_s = 2R_s/c. \quad (10)$$

In accordance with (9) and (10) the scanning rate should be increased so that the condition is met:

$$\varepsilon_{bw} = \Omega t_s \ge \theta_w \text{ or } \varepsilon_{bw} = \Omega t_s = \gamma\theta_w, \quad (11)$$

where the relative scanning rate is

$$\gamma = \varepsilon_{bw}/\theta_w = \Omega t_s/\theta_w \ge 1,$$

i.e., during a signal delay $t_s$ the antenna, its transmitting AP and receiving AP rotate through an angle $\varepsilon_{bw}$ which exceeds the width $\theta_w$ of the receiving AP in the scanning plane ( $\varepsilon_{bw}$

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is $\gamma$ times as much as $\theta_w$ ). However, the boundless increase of the scanning rate (increase of the value $\Omega$ or $\gamma$ ) is not reasonable, since it leads to the spectrum broadening of the radar echoes, their time (Doppler) resolution degradation and, as a consequence, degradation of the Doppler moving target extraction on a clutter background. Our investigations, which go out of the presented paper, allow to conclude that as a rule the optimal parameter $\gamma$ should be equal to 2.5-3.0.

Equation (1) describes the useful signal if, here, $\alpha$ and $R = R_s$ are coordinates of the searched target. Then the last exponential factor in (1) with $t_R = t_s$ and with (11) at the time (3) of the signal maximum is equal to

$$\exp\left\{ j2\pi \frac{x}{\lambda} (\varepsilon_{b0} - \varepsilon_{bw}) \right\}.$$

Therefore, the signal phase does not vary along the antenna aperture (target is disposed at the receiving beam center and the echo signal is received with maximum gain) if

$$\varepsilon_{b0} = \varepsilon_{bw}. \qquad (12)$$

Thus, the principal maximum of the transmitting AP should be rotated at the angle $\varepsilon_{bw}$ relative to the receiving antenna normal (relative to the principal maximum of the receiving AP).

Equation (1) describes the clutter if $\alpha$ and $R << R_s$ are coordinates of the nearby interfering reflector. Assume that at a time $t$ the reflector is disposed at the receiving beam center (at the antenna normal direction). At this time the clutter phase does not vary along the antenna aperture, i.e., $\alpha = \Omega t$ or $t = \alpha/\Omega$ for the last exponential factor in (1). Then another factor in (1) is $G_{b0}\{\alpha - \Omega(t - t_R)\} = G_{b0}\{\Omega t_R\}$. Clutter (1) is sure to be suppressed if the normalized AP value is defined by the inequalities

$$G_{b0}\{\Omega t_R\} << 1 \text{ or } \left|\varepsilon_{b0} - \Omega t_R\right| \geq \theta_b, \qquad (13)$$

where $\theta_b$ is the width of the transmitting AP $G_{b0}\{\varepsilon\}$.

In our case $R << R_s$ or $t_R << t_s$. Then (11)-(13) lead to

$$\theta_b \leq \varepsilon_{bw} = \Omega t_s. \qquad (14)$$

According to (11) and (14), the transmitting and receiving antenna beams should be quite narrow. The obtained results and their use for a solution of the discussed problem (see above) of the space selection of the signals on a clutter background with continuous and quasi-continuous radiation can be interpreted in the following way. Let us assume that antenna system has separate transmitting and receiving APs. While scanning (AP rotation), the main lobes of these APs are displaced in the scanning plane (in the azimuth plane) by the constant angle $\Omega t_s$ with respect to each other. Moreover, the scanning rate $\Omega$ is so high that during a delay $t_s$ of the signal from the farthest target, every scanning AP rotates through an angle $\Omega t_s$ which exceeds the AP width. However, these APs do not have time for a turn between moments of probing and echo reception from nearby land or water surfaces (reception of intense clutter at short and medium ranges). Then this clutter will be reached at angles corresponding to the main lobe of the transmitting AP and, consequently, sidelobes of the receiving AP. I.e., the most intense clutter from nearby interfering reflectors will be attenuated upon the reception. During a delay of the useful signal from a far target, the APs rotate so that the signal is received by the main lobe of the receiving AP. Such reception will lead to a signal gain. So, the signal to noise ratio will rise by value determined by the AP sidelobe level.

Equations (10), (11) and the presented interpretation show that if the scanning rate $\Omega$ and the displacement angle $\varepsilon_{bw}$ of the APs are given, the echo signals are optimally received only with the determinate target range $R_s$. If herewith the value $R_s$ is chosen as the radar maximum range, the result turns out to be similar to the well-known time-controlled gain (but known time-controlled gain cannot be used in the interesting case of continuous or quasi-continuous radar radiation). Yet, when such result is not desired, a parallel (multichannel) or series range scanning is possible. Assume that $\Omega$ is defined and $\gamma = 3$. In this case, with the parallel range scanning, the four receiving channels are requested. The directions (measured from the normal to the antenna) of the principal AP maximums for these channels are equal to $\varepsilon = \varepsilon_{b0} - i\theta_w$, where $i = 0, 1, 2, 3$. With the series range scanning the direction of the principal maximum of the receiving AP relatively to the normal should be varied (for example, periodically), i.e., the displacement angle $\varepsilon_{bw}$ of the main lobes of the transmitting AP and the receiving AP with respect to each other should be varied.

The efficiency of the suggested method of the space clutter suppression is investigated by the mathematical analysis (with optimization of the scanning and the antenna parameters). We present some results.

## IV. Calculation Results

Figs. 1 and 2 present the calculations for the real cylindrical array. Fig. 1 presents the optimized receiving AP (the solid curve) calculated under conditions indicated in our works [2], [5] and at high scanning rate ( $\gamma = 3$ ). Here, the dashed curve is the main lobe of the transmitting AP. Fig. 1 shows that the performed optimization generates the receiving AP in the form necessary for the high quality of the space signal processing on a clutter background with quasi-continuous radiation and at the high scanning rate. Namely, optimized receiving AP (Fig. 1) has following details. Firstly, the main lobes of receiving and transmitting APs are displaced by the constant angle $\Omega t_s$ with respect to each other. Secondly, optimized receiving AP has the low sidelobe level in the region of the transmitting AP main lobe (in the angle

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interval corresponding to the arrival directions of the highest intensity clutter from the close reflectors).

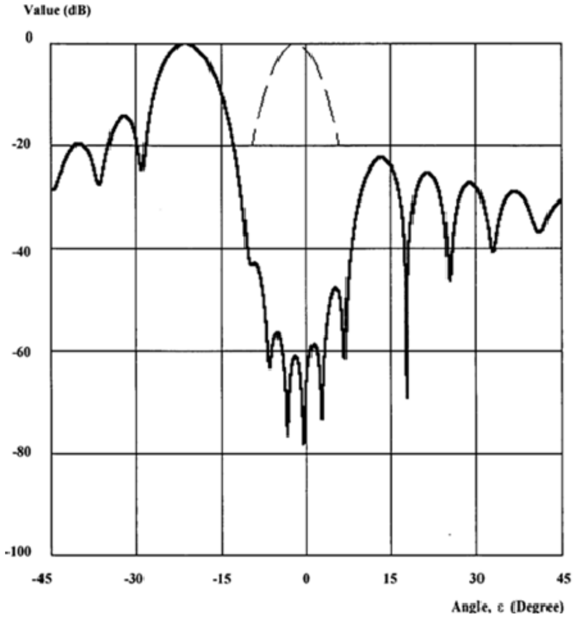


Fig. 1 Results of receiving AP optimization

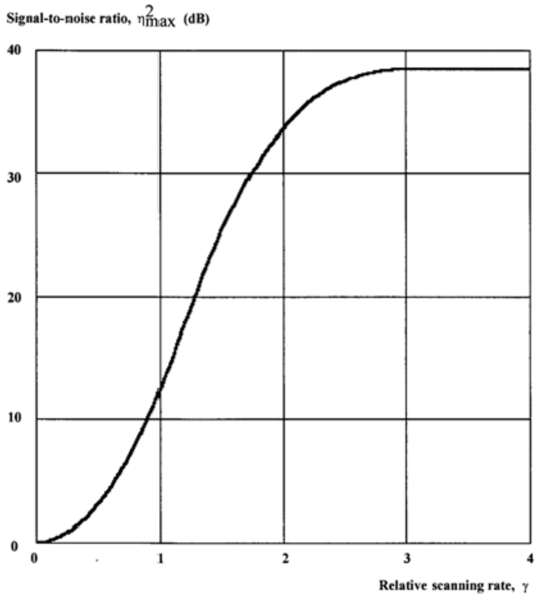


Fig. 2 Signal to noise ratio dependence on scanning rate

In Fig. 2 is presented the maximum attainable signal to noise ratio $\eta^2_{max}$ with respect to relative scanning rate $\gamma$. One can see that the high scanning rate gives the signal to noise improvement (compared to the traditional case when $\gamma << 1$, i.e., the scanning rate is low). This improvement is due to the space signal processing and can achieve the value equal to 38 dB (Fig. 2). However, the high scanning rate leads to the reduction in the time signal processing quality on a clutter background, i.e., to the degradation of Doppler selection (moving target indication) in space-time systems. This efficiency reduction leads to the improvement reduction (especially with the increase of $\lambda$). So, for example, the improvement is reduced to 17 dB for a real noise situation if $\lambda = 0.2$ m, the radar maximum-range equals $3 \cdot 10^5$ m, a transverse Doppler filter is of the order 2 and the optimized transmitted pulse repetition period $T_p = 100\,\mu s$ (in the case of the pulse repetition frequency increase). Thus, the use of the high scanning rate yet gives the meaning signal to noise improvement for the space-time signal processing.

## V. Conclusion

The high scanning rate (compared to the traditional scanning rate values) provides the range-to-angle conversion. As a result, in a monostatic radar system the spatial resolution of echo signals, originating at different distances is achieved (in particular, if angular coordinates of the echo reflectors are identical). This spatial resolution is realized by the use of the antenna system. As a consequence, the space-distance signal selection on a clutter background is achieved. Such selection is helpful with continuous or quasi-continuous radiation when weak far range target echoes are received on an intense close clutter background. Moreover, the spatial signal resolution and the mentioned space signal selection are improved not only with the antenna aperture increase or with the AP narrowing (this is a well-known recipe) but also with the high scanning rate. In this sense the high scanning rate is equivalent to the antenna aperture increase and to the AP narrowing.

The cylindrical array use enables us to produce the receiving AP necessary for the high quality space signal processing on a clutter background with high scanning rate. Herewith, analysis shows that scanning rate increasing and array parameters optimization with the continuous or quasi-continuous probing and with the target detection on a clutter background provides a significant improvement in the signal-to-noise ratio (tens of decibels).

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