RESOLVING POWER OF A SIDE-LOOKING RADAR WITH SYNTHETIC APERTURE IN OBSERVING THE SURFACE OF THE SEA

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Constraints on the azimuthal resolving power of a side-looking radar station with a synthetic aperture (RSA), associated with motion of the surface of the sea, are considered. The solution of the problem is based on a two-scale model of uhf signal scattering by the disturbed surface of the sea. Qualitative estimates of the azimuthal resolution of an RSA as a function of the parameters of the station and the condition of the sea are given.

1. Introduction

For a long time it was assumed that it is impossible to obtain an image of the surface of the sea using a side-looking radar with synthetic aperture (RSA). Recent experimental results [1-4] demonstrate that this opinion is erroneous. The images offered in these publications clearly indicate wind waves, ship waves, areas of wind shadow on the surface, etc. Theoretically, however, the process of synthesizing an image of the surface has hardly been considered at all up to now.

In this paper we make an attempt to find constraints associated with the motion of the surface on the azimuthal resolving power of RSA in the centimeter and short decimeter ranges. The following procedure was employed: We examined the process of image penetration for the case of small surface disturbances (much less than the radio wavelength $\lambda$) using the familiar results obtained for the field scattered by a slightly disturbed surface of this type [5, 6]; then the final conclusions regarding the RSA resolutions were made on the basis of a two-scale model of scattering of uhf signals by the turbulent surface [6, 7].

2. Effect of Small Surface Fluctuations

The essential features of synthesizing an image of a moving surface when its deviations from the mean position are small can be conceptualized by employing the following simple reasoning.

Any realization of a stationary random surface can be represented in the form of an array of infinite sinusoids corresponding to some spectral density $\tilde{R}(K_x, K_y)$. Here and henceforth, the $y$ axis is assumed to be directed along the path of the carrier of the RSA. If each of these sinusoids moves with its own phase velocity, corresponding to the dispersion relation $\omega = \Omega(K_x, K_y)$, while remaining absolutely regular in the process, this surface will correspond to a spectral density

$$\tilde{R}(K_x, K_y) f[\omega - \Omega(K_x, K_y)]. \quad (1)$$

Actual fluctuations of the surface of a fluid will correspond to some three-dimensional spectral density, which can always be approximately written in the form

$$\tilde{R}(K_x, K_y) f[\omega - \Omega(K_x, K_y), \gamma(K_x, K_y)], \quad (2)$$

where $f$ is some function whose maximum is at the point $\omega = \Omega$ and has width $\gamma$. For $\gamma \to 0$ we have $f \to \delta(\omega - \Omega)$. Obviously, fluctuations of the surface with spectral density of the form (2) can be associated with an array of sinusoids of finite-length wave trains with random independent phase that move with phase velocity $v_{ph}(K_x, K_y)$ and that exist on average over a time $\tau_0 = \gamma^{-1}(K_x, K_y)$.

Let us consider scattering on the surface in the first approximation of the small-perturbation method. Then, if each train contains at least a few periods and the width of the actual antenna pattern in the azimuthal plane is not greater, we can take account only of trains with wave numbers that lie in a small neighborhood of...
values $K_x = 2k \cos \delta$, $K_y = 0$ ($k = 2\pi/\lambda$, $\delta$ is the grazing angle; $\delta < 60^\circ$); the remaining ones yield virtually no contribution to backscattering [5, 6]. The amplitude of the field scattered by each train is directly proportional to the amplitude of the latter and depends on $\delta$ in a complex fashion. The frequency of the signal reflected toward the station is shifted by an amount $\pm 2k(2k \cos \delta, 0)$ (the sign depending on the direction of the phase velocity of the train, i.e., toward the station or away from it).

When the RSA carrier is in uniform motion, the frequency shift of the signal reflected from a stationary concentrated target is a linear function of the coordinate $y$, while the signal-processing system in the RSA, as we know, can be regarded as a spatial filter that is matched with an LFM signal [8]. The additional constant frequency shift of the LFM signal results in a shift (in this case a spatial shift) of the compressed signal [9], i.e., to displacement of the image of the train with respect to the $y$ axis. The size of the shift is $(r/V)\nu_{ph}(2k \cos \delta, 0) \cos \delta$, where $r$ is the slant range to the target and $V$ is the velocity of the carrier.

Obviously, coherent accumulation of signals reflected from a given train can occur as long as this train exists with its own constant or linearly varying phase. Correspondingly, the azimuthal size of the image of the train will be determined by the synthesis time $t_c$ for $t_c < \tau_0$ and by the time $\tau_0$ otherwise:

$$\Delta y \approx \frac{r}{V} \frac{\lambda}{\min |t_c; \tau_0|}$$

(Regarding the way in which the resolution depends on the synthesis time, see, e.g., [8]).

From all indications, $\tau_0$ is not less than the attenuation time of the oscillations with wave-vector modulus equal to $2k \cos \delta$. If we assume that wave attenuation is governed by the molecular viscosity of the fluid, then [10]

$$\gamma = \frac{2\mu K^2}{\rho},$$

where $\mu$ is the dynamic molecular viscosity of the fluid; $\rho$ is its density; and the condition $t_c < \tau_0$ is satisfied with a large margin for actual systems in the centimeter and short decimeter ranges with parameter $r/V \sim 100$ sec (this value being characteristic of radar stations intended for operation in satellites with medium-level orbits). In the case of actual wind disturbance, the uppermost layer of the sea becomes turbulent, and $\tau_0$ can vary; as before, however, we will assume that impairment of the resolution as a result of the finite "coherence" time of the resonant component of the ripple does not occur.

Thus, we obtain an image of each train with resolution

$$\Delta y_0 = \frac{r}{V} \frac{\lambda}{t_c}$$

that is shifted with respect to $y$ by $(r/V)\nu_{ph}(2k \cos \delta, 0) \cos \delta$. Experiments have shown [11] that surface fluctuations with a wavelength on the order of 10 cm are isotropic even for wind speeds of around 1 m/sec or more, i.e., almost always. Consequently, the intensity of trains moving toward the station and away from it is the same on average, and instead of each of the surface areas with differing ripple amplitude (oil spots, wind shadows), we obtain two images that are shifted with respect to $y$ by $(r/V)\nu_{ph} |\cos \delta$ in different directions from the true position.

Thus, the image of the surface may become "split." Appearance of the splitting effect may be observed when the following conditions are satisfied:

$$\Delta y' < (r/V)\nu_{ph} |\cos \delta$$

where $\Delta y'$ is the resolution of the station resulting from large-wave effects (see below) and the inherent instabilities of the radar station ($\Delta y_0$);

the size of the observed object is less than $(r/V)\nu_{ph} |\cos \delta$.

If we add that $(r/V)\nu_{ph} |\cos \delta$ can exceed $\Delta y'$ only by a few times in the best (and rather rare) situations, then it becomes understandable that essentially the main effect is impairment of resolution, this amounting to

$$\Delta y_t = 2 \frac{r}{V} \nu_{ph}(2k \cos \theta, 0) |\cos \theta = \frac{r \cos \theta}{V} \sqrt{\frac{2g}{k \cos \delta} \left(1 + \frac{4\pi^2 \alpha^2 \cos^2 \delta}{\rho g}\right)}$$

(3)

Here $\alpha$ is the surface tension factor of the fluid.