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AN ESTIMATE OF ARRIVAL TIMES AND ANGLES OF LOW-FREQUENCY SURFACE PREREVERBERATION IN THE OCEAN

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Abstract - Prereverberation caused by sound scattering from the rough ocean surface is considered. For low-frequency scattering described by the first approximation of the small perturbation method, the arrival times and angles of prereverberation signals in the surface sound channel are analytically estimated and numerically calculated as functions of the wind speed, sound frequency, and distance. The obtained estimates agree with data of the in-sea experiments.

The prereverberation phenomenon detected experimentally in the 1960th [1] consists in earlier signals arrivals, than it follows from "classic" calculations, to the distant point of reception. Prereverberation is caused by sound scattering from inhomogeneities of the sea surface, bottom and water column of the ocean. A model for the prereverbation caused by scattering of high-frequency sound from the sea surface has been considered in Ref. [2]. Here, we present simple estimates of the arrival times and angles of prereverberation caused by scattering of low-frequency sound (as long as the Rayleigh parameter P is small) from the ocean surface.

The scattering diagram (that is, angular distribution) of the intensity of the surface-reradiated field at $P^2 << 1$ has one or several maxima. For fully developed isotropic sea roughness described by the Pierson-Moscovitz spectrum, in the first approximation of the small perturbation method, explicit expressions were obtained [3] for the angles corresponding to peaks of the scattering diagram, as well as for the peak width, these estimates being valid for nearly all situations occurring at $P^2 << 1$. One of the expressions which is valid provided that $|c - c_0| << 1, |c - c_0| \cdot ctg c_0 / 2 << 1$

has the form
$$|\cos c_m - \cos c| = \frac{K_m}{\sqrt{2k}}. \quad (1)$$

Here, c_0 is the grazing angle of an acoustic wave incident on the surface, c_m are the grazing angles corresponding to the diagram maxima (due to the modulus in the left-hand side of expression (1), there are, in general, two such maxima), k is the sound wave number, and $K_m \approx 0,61g/v^2$ is the wave number of a surface gravity wave corresponding to maximum of the Pierson- Moscovitz spectrum (g = 9. 81 m/s^2, v is the wind speed expressed in m/s, the dimension of K_m is 1/m). Expression (1) determines the Bragg diffraction spectra of the first order in scattering from the surface harmonic corresponding to the maximum of the roughness spectrum.

Restrict ourselves to the consideration of the subsurface channel with the vertical gradient of sound speed c so that $c(z) = c_0(1 + az)$ where c_0 is the sound velocity at the surface, z is the depth (in the example presented below $a = 1.1 \cdot 10^{-5}$ 1/m). Assume that the source S (see Fig. 1) and receiver R are located near the ocean surface, at the distance $r = r_1 + r_2$ apart. On the source-to-receiver propagation path, sound is single-scattered from the surface (at the point O in Fig. 1), and the grazing angle c_0 of the ray incident on the surface is not equal to that of the scattered ray: the latter corresponds to the direction c_m of the scattering diagram maximum, as given by expression (1). Along with two ray cycles shown in Fig. 1, which correspond to the condition $c_0 < c_m$, two other cycles are possible with $c_0 > c_m$ that differ from the shown cycles only by the order in which one is followed by another.

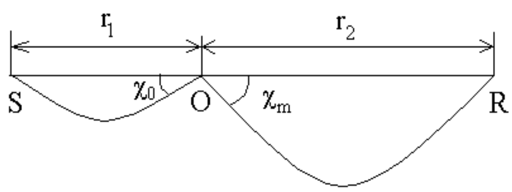

Fig. 1.

Denoting $b = r_1/r_2$, using simple geometric considerations, and retaining terms up to the order of c_0^2 and c_m^2 (the grazing angles are small), we obtain from formula (1):

$$
\begin{aligned}
c_0 + c_m &= \frac{ar}{2}, \\
c_0 &= bc_m, \\
\left|c_0^{\,2} - c_m^2\right| &= \frac{\sqrt{2}K_m}{k}.
\end{aligned}
\tag{2}
$$

These three equations serve to find three unknown quantities (c_0, c_m, and b) from the known distance r, gradient a, wave number K_m of the maximum of the roughness spectrum (i. e., wind speed), and the sound wave number k (i. e., sound frequency).

System (2) can be easily resolved yielding
$$
c_m = \frac{ar}{4} \pm \frac{\sqrt{2}K_m}{ark}, \quad c_0 = \frac{ar}{4} \mp \frac{\sqrt{2}K_m}{ark}, \tag{3}
$$

for the grazing angles of the incident and scattered rays. Here, the upper sign refers to the case $c_m > c_0$ while the lower sign refers to the case $c_m < c_0$. Note that the quantity corresponding to the minus sign in the right-hand side of formula (3) must be positive. For given values a, K_m, and k, this fact limits the minimum distance, for which the situation shown in Fig. 1 can be realized; for smaller distances, there are no values c_0 and c_m that can be described by formula (1). The higher the sound frequency (larger k) and the larger the wind speed, the less severe the condition that this difference would be positive. Substituting (3) in the second equation of system (2) yields the estimate for the ratio $b = r_1/r_2$.

The ray geometry shown in Fig. 1 refers to the earlier arrival of signals to the point of reception, as compared to the case of specular sound reflection from the sea surface when $r_1 = r_2$. For small grazing angles, this advance can be determined from the approximate formula [2]

$$
Dt \approx T_0\left[1 - 4\,\frac{r_1}{r} + 4\left(\frac{r_1}{r}\right)^2\right], \tag{4}
$$

where
$$
T_0 = \frac{a^2 r^3}{32 c_0}.
$$

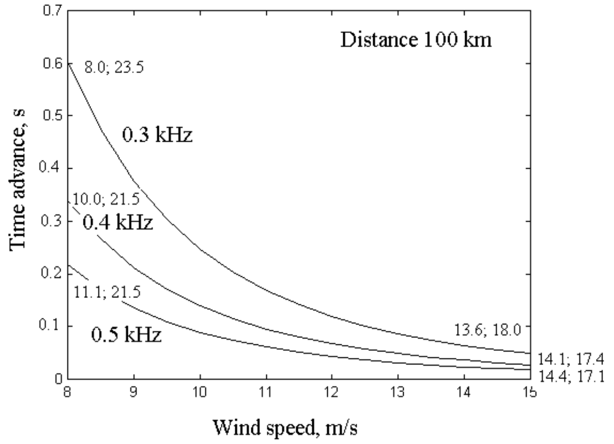

Fig. 2.

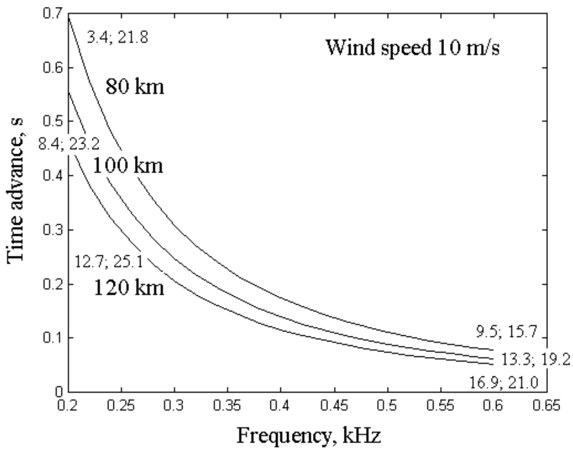

Fig. 3.

In view of the relation $r_1/r = b/(1 + b)$, formula (4) can be easily applied to the considered case.

Figure 2 shows the dependences of the prereverberation time advance Dt on the wind speed, at the fixed distance (r = 100 km), for three sound frequencies (0. 3, 0.4, and 0. 5 kHz as indicated in Fig. 2). Small numbers shown near the left and right ends of each curve denote the angles c_0 and c_m (or c_m and c_0, in degrees) calculated for the wind speeds considered. Note that distances shown in this and subsequent figures can be not feasible because of finite waveguide depth.

The dependences of the prereverberation time on the sound frequency, which are calculated for the wind speed 10 m/s and three distances (80 100, and 120 km), are shown in Fig. 3 (the pair of numbers near curves has the same meaning as in Fig. 2). Finally, Fig. 4 shows the range dependences of the prereverberation time (and angles c_0 and c_m) for the wind speed 10 m/s and sound frequencies 0.3 - 0.5 kHz. Note that the calculated values of *Dt* agree with the experimental data (in particular, with those mentioned in Ref. [4]).

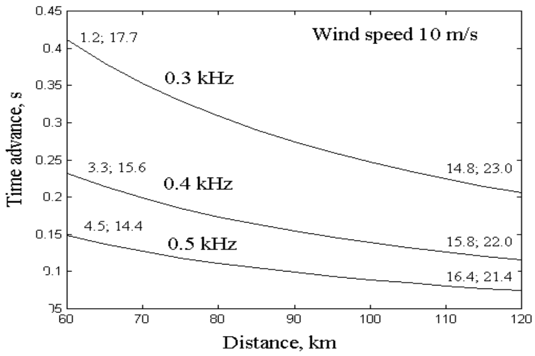

Fig. 4.

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