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Specific features of surface reverberation in shallow water with focused sound field

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The specific features of long-range low-frequency (230 Hz) surface reverberation using vertical radiating array are studied in the framework of numerical experiment. We assume that the array focuses a sound field at different distances from ruffled surface in shallow water. Focusing is carried out by using a time-reversal mirror at a distance 10 – 30 km from radiating array. We consider sound focusing and surface reverberation in the presence of intense wind waves for acoustic waveguide common to shallow water for different seasons. The feasibility of surface reverberation suppression is estimated by sound focusing in the central region of the waveguide including the region located below thermocline. The results of numerical modeling are compared with the similar results obtained before for bottom reverberation.

1 Introduction

It is known that long-range low-frequency reverberation in a shallow sea is mainly formed due to sound scattering by the sea bottom. Hereafter, reverberation at frequencies of hundreds of Hertz, occurring during backscattering of acoustic waves at a range of several tens of kilometers from a sound source is kept in mind. However, this statement is by no means always valid. In particular, surface reverberation can exceed bottom reverberation at intense surface roughness in regions with a relatively smooth sandy bottom with a small backscattering coefficient [1]. Such a case is most probable in winter time, when the sound speed in a shallow waveguide depends weakly on depth. The dominance of surface reverberation can also be expected when the sound field is focused to the waveguide surface region using vertical radiating arrays [2, 3].

This paper is devoted to an analysis of long-range reverberation as applied to exactly such cases, when the received reverberation signal is related to both backward and forward sound scattering by the sea surface. In this case, forward sound scattering in the problem at hand is no less important than backscattering. This is because both incident and scattered acoustic waves travel a significant distance between the radiating array and scattering area, interacting with the rough sea surface. We also note that long-range bottom reverberation for focused radiation was already considered in many papers (See for example [2,3]). However, the obtained results do not allow estimation of surface reverberation features for two causes. First, the theory and procedure for calculating sound backscattering by the sea surface and sea bottom are different. This is because the field incident on the sea surface in the acoustic waveguide is zero in the zeroth approximation. Second, the interaction of sound with a rough sea surface during further propagation was neglected in calculations [2, 3].

2 Basic relations

The mode description of the sound field was used for simulating surface reverberation. Focusing was achieved due to phase conjugations of a sound wave from a probe source placed at the focusing point.

A waveguide of constant depth H was considered. The origin of the cylindrical coordinate system was on the waveguide upper surface. The vertical z axis was directed downward. Elements of the linear transceiver array had coordinates $(0, z_j)$, $j = 1,...,J$ (J is the number of elements). The transceiver array emitted a pulsed signal and was tuned to focusing at the point (r_0, φ_0, z_0). On the assumption of a narrow-band signal, all parameters of incident and scattered fields were considered only for the center frequency f_0.

For the complex amplitude $p_s(\vec{R}_j, \vec{R}_s)$ of a sound field scattered by the elementary area ds $(ds = r_s dr_s d\varphi)$ of the sea surface, the incident field expansion in the small parameter ζ was used. The parameter ζ is the random deviation of the sea surface from the equilibrium position. $\vec{R}_j$ is the radius vector of the sound source and receiver (it is assumed that they are combined) in the array $\vec{R}_j = z_j \vec{n}_z$, $\vec{R}_s$ is the radius vector of the elementary scattering area of the sea surface, $\vec{R}_s = r_s \vec{n}_r$. In this case, it was assumed that $P << 1$ (P is Rayleigh parameter. $P = (4\pi\zeta \sin\theta)/\lambda$, θ is sliding angle, λ is sound wavelength) and the emission duration is sufficiently short, such that for the time equal to the sound pulse duration the value of ζ is unchanged. As a result, the following expression for $p_s(\vec{R}_j, \vec{R}_s)$ can be written [4],

$$p_s(\vec{R}_j, \vec{R}_s) = \zeta(\vec{R}_s) \frac{\partial \widetilde{G}(\vec{R}_s)}{\partial z} \frac{\partial G(\vec{R}_s, \vec{R}_j)}{\partial z} ds \qquad (1)$$

where $G(\vec{R}_s, \vec{R}_j)$ is the waveguide Green's function, , and $\widetilde{G}(\vec{R}_s)$ is the sound field incident on the scattering area,

$$\widetilde{G}(\vec{R}_s) = \sum_j^J A_j G(\vec{R}_j, \vec{R}_s) \qquad (2)$$

where A_j is the coefficient defined by the radiation power and depending on the amplitude-phase distribution of the probe source field over the array aperture.

It is known that for the shallow waveguide with a rough upper boundary, placed at a constant depth, and characterized by an unchanged sound speed profile, the Green's function can be written as [5]

$$G(\vec{R}_j, \vec{R}_s) = \sum_m^M C_m(r_s, \varphi, T) \frac{\psi_m(z)\big|_{z=0}}{\sqrt{r_s q_m}} \exp(i q_m r_s) \qquad (3)$$

$$G(\vec{R}_s, \vec{R}_j) = \sum_\mu^M C_\mu(0, \varphi, T) \frac{\psi_\mu(z_j)}{\sqrt{r_s q_\mu}} \exp(i q_\mu r_s) \qquad (4)$$

for incident (3) and scattered (4) fields, respectively. Here T is the time which, on the assumption of time-independent medium, enters formulas (3) and (4) as a parameter; M is the number of modes; $\psi_m(z)$ and $\xi_m = q_m + i\gamma_m/2$ are the eigenfunction and the propagation constant of the $m-$th mode; and the angle φ defines the direction to the elementary scattering area. The coefficients C_m and C_μ are determined by solving a set of equations of coupling modes at the distance from the transceiver array to the scattering area on the sea surface [5]:

$$\frac{dC_m(r',\varphi,T)}{dr'} = -\frac{\gamma_m}{2} C_m(r',\varphi,T) + i\sum_{n=1}^{M} v_{nm}(r',\varphi,T) C_n(r',\varphi,T) \times \exp(i(q_n - q_m) r') \tag{5}$$

with the mode coupling coefficients[1] ν_{mn}.

$$\nu_{nm}(r',\varphi) = \zeta(r',\varphi,T) \frac{1}{2\sqrt{q_n q_m}} \frac{\partial\psi_m(0)}{\partial z} \frac{\partial\psi_n(0)}{\partial z} \tag{6}$$

The dependences of the function $G(\vec{R}_s,\vec{R}_j)$ on $\vec{R}_j$ in formula (3) and on $\vec{R}_s$ in formula (4) are controlled by boundary conditions specified at points with coordinates $(0,z_j)$ and $(r_s,0)$ for the coefficients C_m and C_μ, respectively.

Using relation (3), we can write formula (2) as

$$\widetilde{G}(\vec{R}_s) = \sum_{m}^{M} C_m(r_s) \frac{\psi_m(z)\big|_{z=0}}{\sqrt{r_s q_m}} \exp(i q_m r_s) \tag{7}$$

where the boundary conditions for coefficients C_m are written as

$$C_m(0,T) = \sqrt{VW_0}\exp(i\pi/4) \times \sum_{j=1}^{J} \sqrt{\rho_j c_j}\, w^*(0,\varphi_0,z_j)\psi_m(z_j) \tag{8}$$

Here $w(0,\varphi_0,z_j)$ is the complex amplitude of the sound field at the point $(0,z_j)$ from the probe point source of unit power, placed at the focusing point (r_0,z_0,φ_0); the sign "*" means complex conjugation (see [3] for more details); $V = \left[\sum_{j=1}^{J} \left|w(0,z_j)\right|^2\right]^{-1}$ is the coefficient determined from the condition $W_0 = \sum_{j=1}^{J} W_j$, where W_0 and $W_j = VW_0\left|w(0,z_j)\right|^2$ are the total power of the array and of its *j*-th element; ρ_j and c_j are the density and sound speed at depth z_j.

The boundary conditions for the coefficients C_μ are written as

$$C_\mu(r_s) = \frac{\exp(i\pi/4)}{\sqrt{8\pi}} \psi_\mu(z)\big|_{z=0} \tag{9}$$

Substituting then relations (3), (4), (7) into formula (1), we obtain:

$$p_s(\vec{R}_j,\vec{R}_s,T) = \frac{\exp(i\pi/4)}{\sqrt{8\pi}} \psi_\mu(z)\big|_{z=0} \times \sum_{m,\mu}^{M} C_m(r_s,\varphi,T) \frac{1}{r_s\sqrt{q_m q_\mu}} \psi_\mu(z_j) \frac{\partial\psi_m(0)}{\partial z} \frac{\partial C_\mu(0,\varphi,T)}{\partial z}\Bigg|_{z=0} \times \exp\big(i(q_m + q_\mu)\big) \tag{10}$$

[1] For the coefficients C_μ formulas (5) and (6) can be written similarly.

where the derivative $\left.\frac{\partial C_\mu(0,\varphi,T)}{\partial z}\right|_{z=0}$ is understood as the derivative at the scattering point, determined from boundary conditions (9). Then, for a narrow-band signal, let us write the expression for the amplitude of the total scattered field received at the point defined by the radius vector $\vec{R}_j$,

$$P_s(\vec{R}_j,r_s) = \int_0^{2\pi} \int_{r_s-\Delta r/2}^{r_s+\Delta r/2} p_s(\vec{R}_j,r_s,\varphi) r_s\, dr_s\, d\varphi \tag{11}$$

where r_s is the effective distance to the sea-surface scattering area being a planar ring of width $\Delta r = c\tau/2$, where *c* is the sound speed.

Formulas (10) and (11) are the basic relations used for calculating surface reverberation, taking and without into account mode coupling on the rough surface. For simulating a random realization $\zeta(r,\varphi)$, we used the known spectrum of intense sea roughness, proposed by Neumann.

3 Initial data for numerical simulation

For calculations, a waveguide with parameters corresponding to the Atlantic shelf of the USA was chosen. The waveguide depth was assumed to be $H = 72$ m. Numerical simulation was performed for two depth dependences of the speed of sound, shown in Fig. 1. These dependences correspond to typical vertical sound speed profiles for winter and summer seasons of the year.

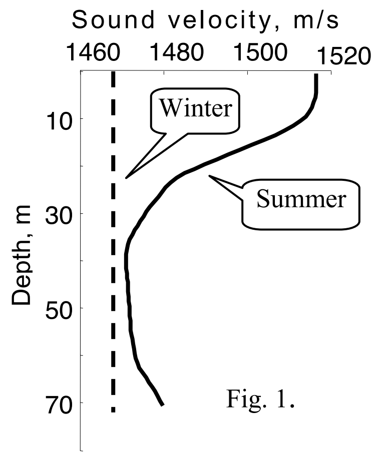

Fig. 1.

It was assumed that the bottom is a homogeneous liquid halfspace with the parameters: the sound speed is $c_1 = 1800$ m/s, the density is $\rho_1 = 1.9$ g/cm^3, the sound attenuation coefficient in the bottom is $\beta = 0.09$ dB/(km*Hz). The sound frequency was chosen equal to $f_0 = 230$ Hz. The array radiation power was $W_0 = 2$ kW. The pulse duration was $\tau = 0.1$ s. It was assumed that the transceiver array covers the entire waveguide. The depths of array elements was $z_j = 72 - 3j$ m, $j = 0,1,...,24$. The wind speed v was varied in the range from 0 to 9 m/s.

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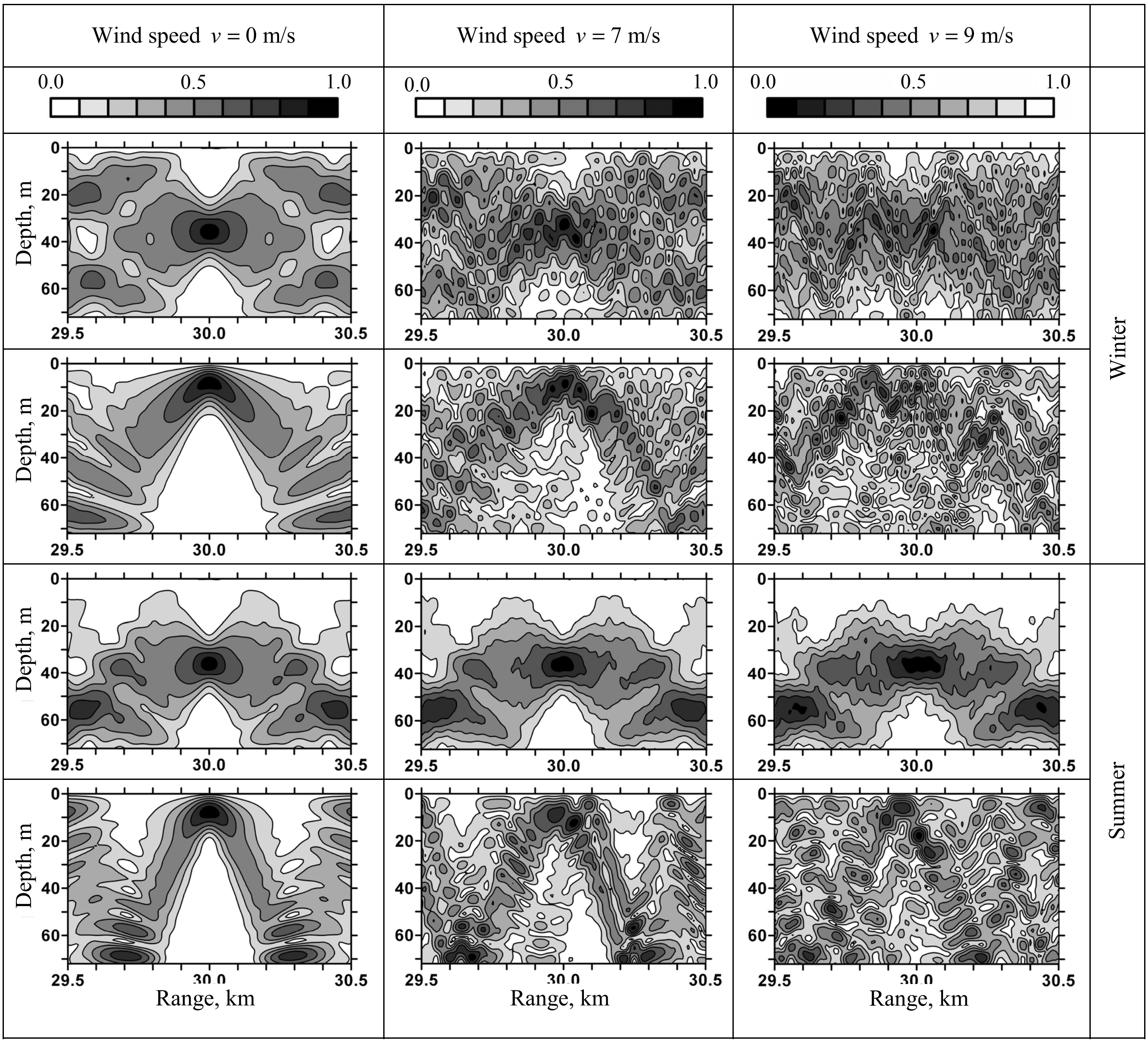

Fig. 2. Sound field magnitude in the region of focusing point in brightness form. In the first and third row the focusing depth is equal to $z_0 = 36$ m. In the second and fourth row the focusing depth is equal to $z_0 = 6$ m.

The random variable ζ was initially calculated in the Cartesian coordinate system with a distance step of 0.5 m The method of simulating random oscillations ζ in the field of surface waves at a known spectrum of these oscillations is described in [6].

4 Calculated results and conclusions

The magnitude distribution of the focused sound field for various sound speed profiles is shown in Fig. 2 without surface roughness (the wind speed is $v = 0$ m/s) and with intense roughness (the wind speed is $v = 7$ and 9 m/s) at $\varphi_0 = 0^\circ$. (The magnitude is normalized to the maximum value). During numerical simulation of these distributions, it was assumed that $w(0, \varphi_0, z_j)$ is time-independent and corresponds to the probe source field in the absence of perturbations in the waveguide. In practice, this value can be measured at corresponding time averaging of instantaneous values of the amplitude and phase of the signal from the probe source. As seen in the figures, it appears possible to focus the sound field in the waveguide under consideration at distances of 30 km from the transceiver array at a wind speed not exceeding 7 m/s independently of the vertical sound speed. At high wind speeds, the focusing quality notably deteriorates. An exception to this general statement is observed for focusing to the waveguide center (under thermocline) to depth $z_0 = 36$ m under summer conditions. This is apparently due to the fact that the sound field is formed by low-damping bottom modes weakly interacting with the sea surface under such conditions [5].

These features of sound field focusing also affect the level of long-range surface reverberation for focused radiation. The results of numerical simulation of the depth-averaged intensity of the scattered field:

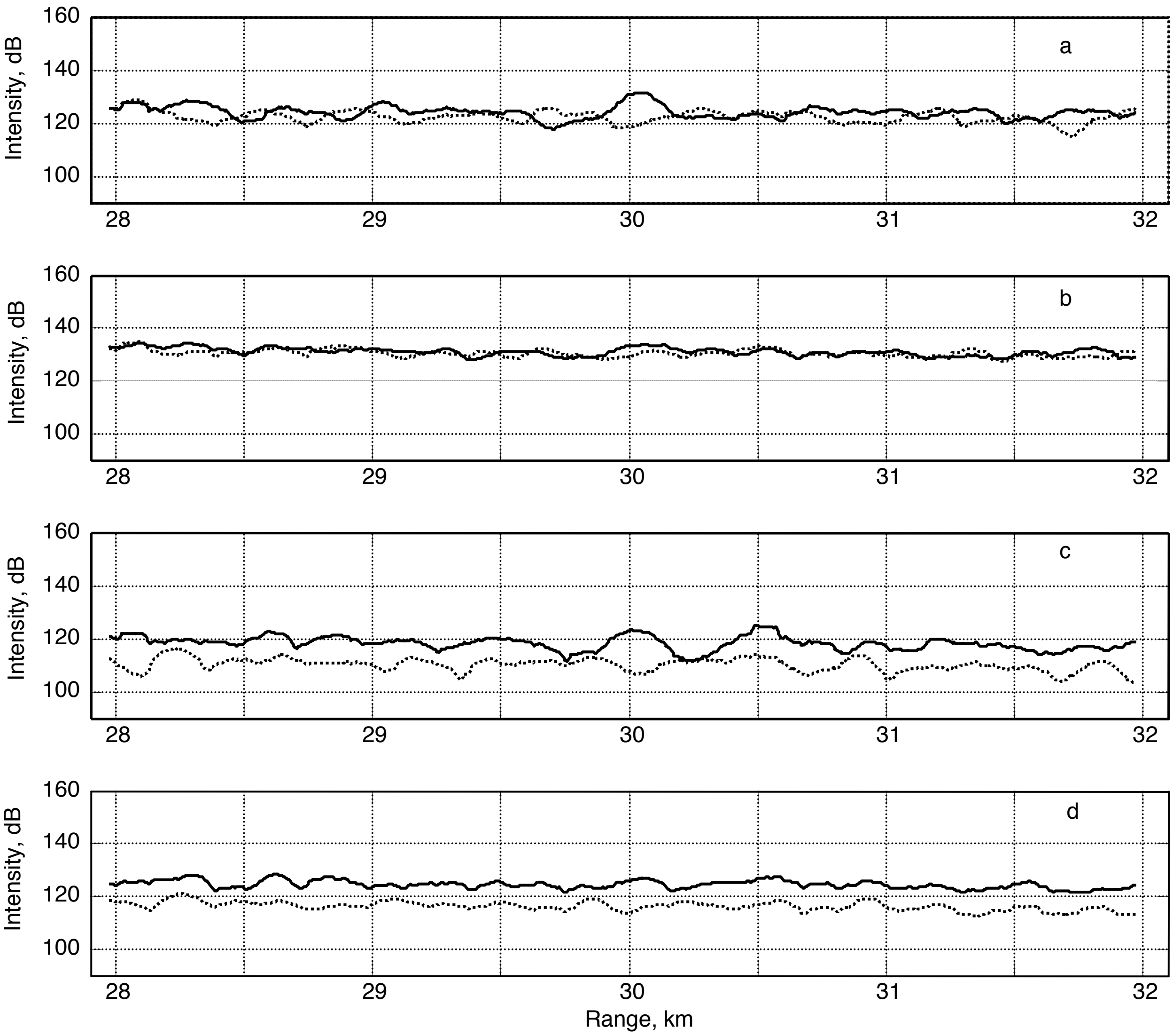

Fig.3. Dependences of the reverberation level on the range to the scattering area with the focusing at the depth z_0 = 36 m (dashed curves) and at the depth z_0 = 6 m (solid curves). (a) $v = 7$ m/s, winter; (b) $v = 9$ m/s, winter; (c) $v = 7$ m/s, summer; $v = 9$ m/s, summer

$$I(r_s,T) = \frac{1}{J}\sum_{j=1}^{J}\frac{\left|P_s(r_s,z_j,T)\right|^2}{\rho_j c_j} \tag{12}$$

are shown in Fig. 3. These dependences of scattered signal intensity on the distance were smoothed by a sliding window 100 m wide as well. This is approximately equal to the horizontal size of focal spot. As can be seen, mode coupling has a significant effect on the surface reverberation intensity and significantly decreases the possibility of suppression of long-range surface reverberation due to sound field focusing to the waveguide center ($z_0 = 36$ m). This fact is explained by that both the level of the backscattered sound field near the scattering area and the coefficient ν_{nm} similarly depend on the surface roughness height (see (1) and (5)). Thus, the situation radically differs from that for long-range bottom reverberation [3] when, in the absence of perturbations in the waveguide, associated with surface or internal waves, the reverberation level can be varied significantly by focusing the sound field to the sea bottom or surface. In fact, the possibility of such reverberation control during intense roughness is retained only in summer time.

Finally, we note that, since the energy transfer from mode to mode increase with range, the possibility of controlling the long-range reverberation level accordingly decreases as receding from the array.

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