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Sound focusing and scanning in shallow water with background internal wave field

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Sound field focusing and scanning with focal spot are investigated for shallow water and long distances (up to 30 km). It is studied the availability of horizontal and vertical scanning for controlling long-range low-frequency bottom reverberation as well. These researches are carried out by using numerical modeling for typical acoustic waveguides including random ones with background internal waves. The acoustic field is focused with vertical array by phase conjugation of sound wave from probe source placed at preset point. Horizontal scanning with the focal spot is performed by radiation frequency tuning. It is demonstrated that the best feasibility for the scanning and hence for controlling bottom reverberation takes place for the regular waveguide under winter conditions when sound speed depends on depth only slightly and background internal waves are nonexistent practically. As an example for these conditions we can control the bottom reverberation on interval ~ 5 km in the neighborhood of a preset point. In summer for near bottom sound waveguide the range of distances for which it is practicable is much narrower even without internal waves. For the waveguide with intense background internal waves the control of long-range bottom reverberation becomes impossible.

1 Introduction

In studying the shelf areas of the World Ocean by acoustic methods, it is sometimes convenient to use focused radiation, i.e., to concentrate the sound field in a certain region, more precisely, in the focal spot area. The sound field can be focused using vertical transceiver arrays with time reversal of the acoustic signal from a point probe source placed at an expected focusing point. For instance, this procedure is applied to control the intensity of sound waves scattered at the boundaries of a shallow-water waveguide. As the focal spot recedes from the boundary, the intensity is lowered [1,2], i.e., long-range reverberation level decreases. On the contrary, we can concentrate the sound field at the waveguide boundary and, using the intense scattered signal, study average characteristics of scattering objects, in particular, the sea bottom. In the latter case, scattered signal fluctuations also carry information on variations in integral characteristics of a medium between the focusing array and a scattering area of the sea bottom shaped as a ring encircling the vertical array. It is also important that the focal spot range in the shallow waveguide characteristic of the sea shelf can be changed in horizontal by retuning only the carrier frequency of array radiation [3]. Focal-spot scanning is understood as its displacement with respect to an initial focusing point along the horizontal line crossing the focal spot and vertical array. In this case, the focusing and scanning quality significantly depend on hydrological conditions.

In this paper, focal-spot focusing and scanning in the wintertime and summertime in shallow water at long distances up to 30 km are studied using numerical simulation. A feature of the wintertime is the weak depth dependence of the temperature and of the sound speed in water; in the summertime, vertical profiles of the temperature, therefore, of the sound speed have appreciable negative gradients. Moreover, as a rule, intense internal waves (IW) occur in the summertime due to the existence of the thermocline which leads to sound speed fluctuations. For these conditions, bottom reverberation during focal-spot scanning at various depths is also analyzed.

2 Computing method and data for numerical experiments

A normal mode model of a sound field is implemented to simulate low-frequency sound propagation and scattering by the bottom in a shallow water. For summertime conditions, the mode coupling caused by background internal waves is taken into account. The basic calculation relations are presented in [2].

In the calculation, it is assumed that the waveguide depth is constant and equal to 72 m. The sound speed in the waveguide varies with depth as is shown in Fig.1. The bottom is considered to be a homogeneous liquid medium with the parameters: the sound speed is 1800 m/s, the density is 1900 kg/m^3, the sound attenuation coefficient in the bottom is 0.18 dB/(km*Hz), and the parameter characterizing the bottom scattering properties is 0.11. As in [2], sound speed fluctuations are simulated using the frequency energy spectrum of random vertical displacements of liquid in the field of background IW given in [4]. We note that some of the above parameters for the calculation (the sea depth, sound speed profile under summertime conditions, and the spectrum of vertical displacements of liquid) correspond to the data of the natural experiment performed on the New York shelf [5].

We consider the transceiver array as a chain of 25 equidistant transceivers covering the entire waveguide over depth. The emitted sound frequency is $f_0 = 230$ Hz, the pulse duration is 3 s, and the total power of the array radiation is 2 kW.

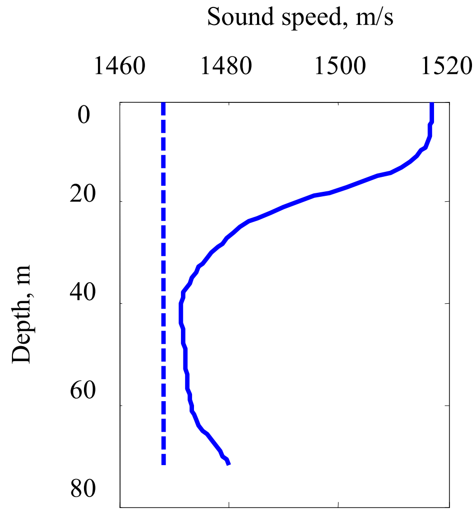

Fig.1. Depth dependences of the sound speed in water for summertime (solid curve) and wintertime (dashed line) conditions.

3 Numerical simulation

3.1 Focusing and scanning

Initial focusing points in the simulation are positioned at distance $r_0 = 30$ km from the array at depths of 36 and 72 m. Without IW, good focusing quality takes place for winter and summer hydrology despite sound attenuation in the bottom. However, with strong IW the focusing quality is degraded. For example, the sound pressure magnitudes in the focal spot region for wintertime and summertime (with strong IW) conditions are shown at the center of Fig.2a and Fig.2b, respectively.

The possibility of changing the focal spot position in horizontal by retuning only the carrier frequency without changing the amplitude-phase distribution over the array aperture is shown in Fig.2a and Fig.2b for the cases of the constant sound speed and the dependence of the sound speed on the waveguide depth in the presence of background IW, respectively. In these figures, we can trace the focal spot displacement Δr along the horizontal line crossing the initial focusing point and transceiver array. As follows from the theory of this phenomenon (see [3,4] and references therein), this displacement corresponds to the sound field interference invariant β existing in the waveguides under consideration. We recall that for modes with the same dispersion relation, the interference invariant is given by

$$\beta = (\Delta f / f_0)/(\Delta r / r_0) = -d[1/c_m^{ph}]/d[1/c_m^{gr}], \qquad (1)$$

where Δf is the frequency retuning, c_m^{ph} and c_m^{gr} are the phase and group velocities of the m-th mode with respect to which the modes forming the sound field at distance r_0 are in-phase.

We note that when the carrier frequency is retuned to 10 Hz in the waveguide with wintertime characteristics, the

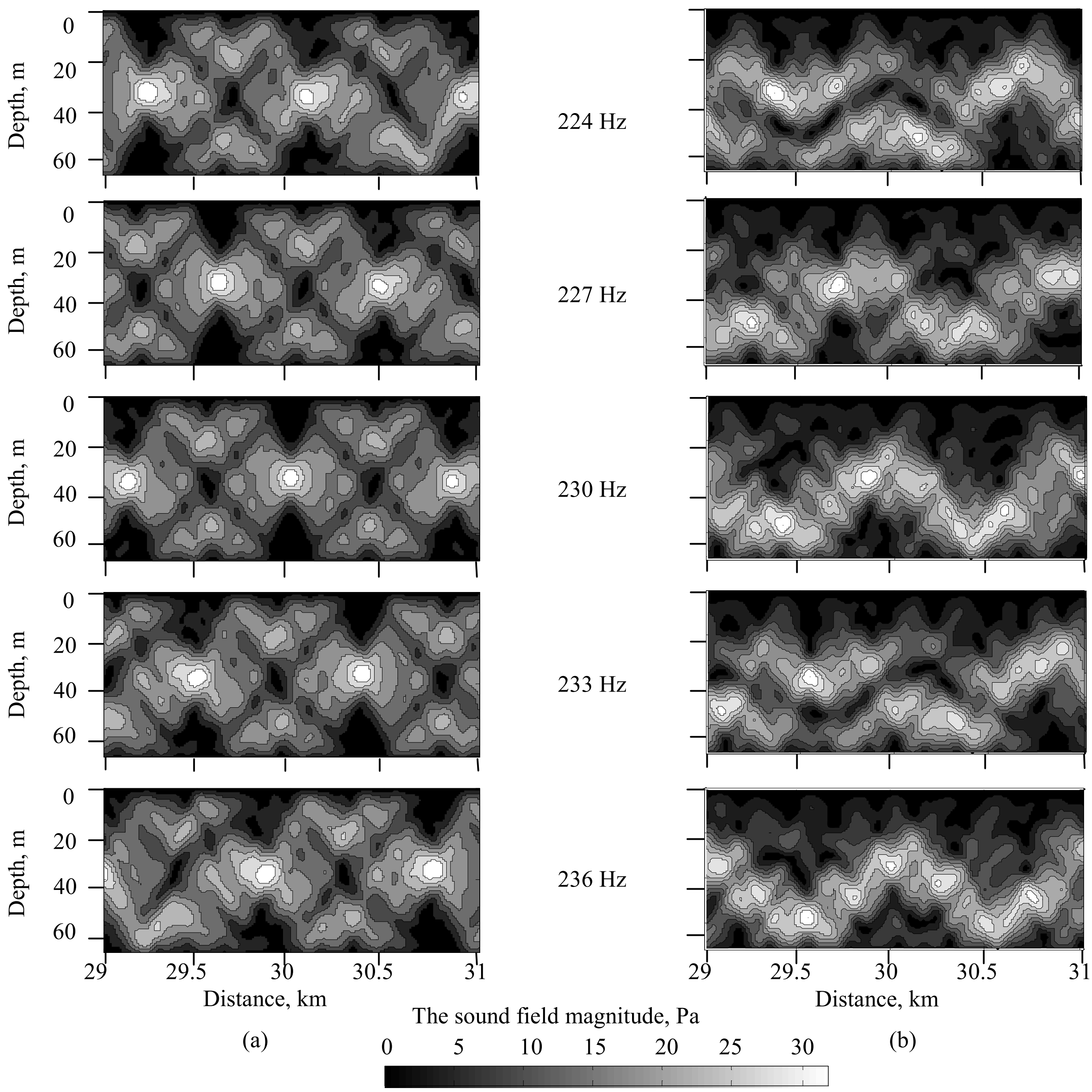

Fig.2. Focal-spot focusing and scanning at a distance of 30 km from the sound source for wintertime (a) and summertime conditions with intense internal waves (b).

focusing spot shape remains almost unchanged. In the case of summertime conditions, the focusing quality degrades rather rapidly with frequency. This is because of the existence of two waveguide mode types in the summertime, i.e., bottom and bottom-surface ones corresponding, respectively, to different interference invariants, $\beta \cong 3$ and $\beta \cong 1$. Thus, in the summertime, there exists a certain effective coefficient β which depends on the ratio of magnitudes of the above modes and retains its value in a much narrower distance range in comparison with the wintertime waveguide where only bottom-surface modes exist and $\beta \cong 1$. In the case of intense IW, the focal spot degrades even more rapidly, which makes impossible horizontal scanning only by retuning the array carrier frequency.

3.2 Bottom reverberation

Within the numerical experiment on the study of bottom reverberation, the complex amplitude of the scattered signal $p^{sc}(r, z_j)$ is determined for each receiving element of the array; then, using Eq.(2), the intensity I of this signal averaged over the array aperture is calculated.

$$I = \frac{1}{J}\sum_{j=1}^{J}\frac{\left|p^{sc}(r, z_j)\right|^2}{\rho_j c_j}, \qquad (2)$$

where J is the number of array receivers, ρ_j and c_j are the density and sound speed at the hydrophone depth z_j. The obtained dependences of the scattered signal intensity on the distance are smoothed by a sliding window 100 m wide which is approximately equal to the horizontal size of the focal spot. The results of the average intensity calculations for the cases of focusing at a frequency of 230 Hz and a distance of 30 km to the scattering area are shown in Fig.3 and Fig.4 (wintertime hydrology and summertime conditions with intense strong internal waves, respectively). The dashed curve corresponds to sound field focusing to the bottom; the solid curve corresponds to focusing to the waveguide enter. As follows from this figure, pronounced maxima and minima of the reverberation signal level are observed when the field is localized to the bottom and center, respectively. This shows the possibility of controlling the bottom reverberation by receding or approaching the focal spot to the bottom surface even at the distance to the scattering area of tens of kilometers. It is important that, when the carrier frequency is retuned without changing the amplitude-phase distribution over the aperture, these extrema are retained and horizontally displaced following the focusing point (Fig.5). The carrier frequency is retuned in the range of 230±15 Hz with a step of 0.25 Hz. To determine the range of distances which we can displace the focal spot within, hence, control the scattered signal level, the ratio $K = \left|p_c^{sc}\right| / \left|p_b^{sc}\right|$ of average magnitudes of scattered field is introduced and calculated for the points corresponding to

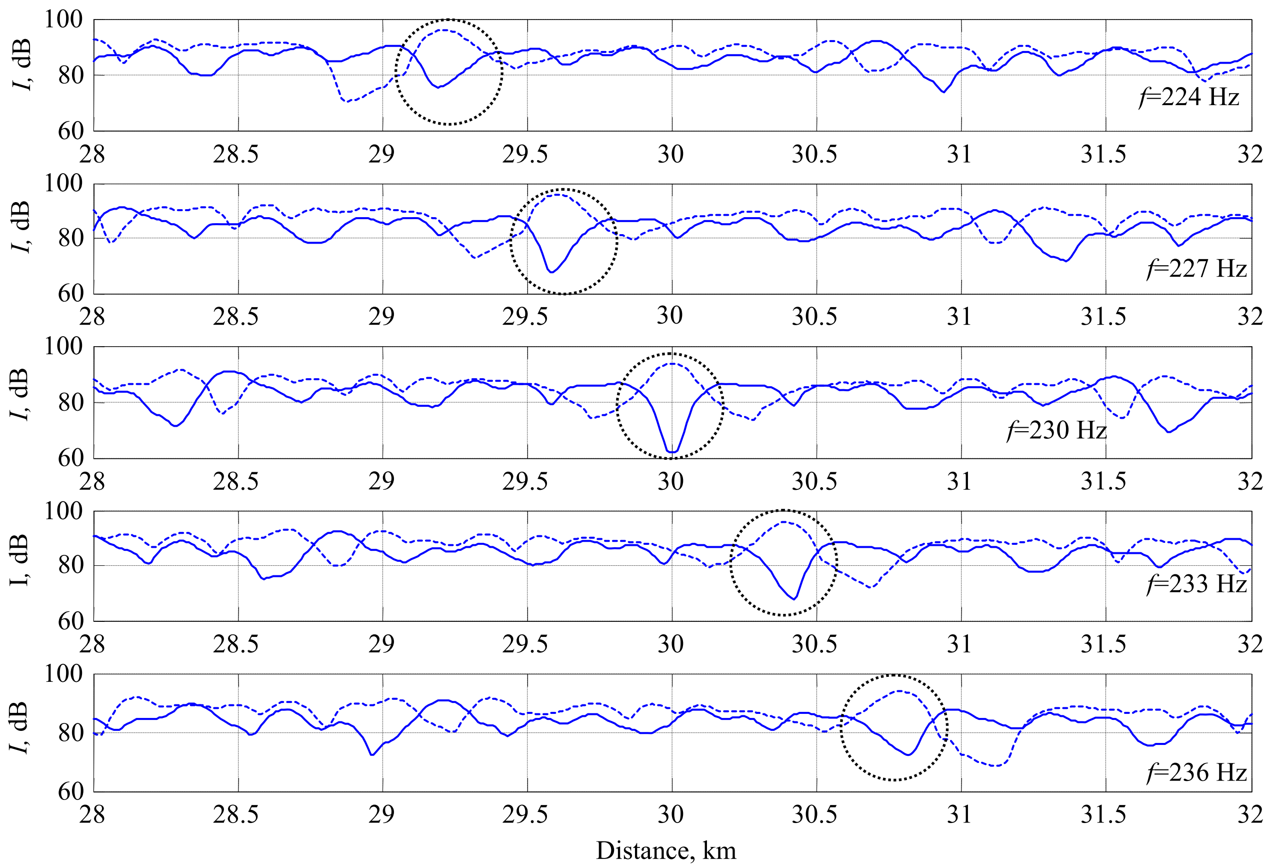

Fig.3. Dependence of the scattered field intensity on the distance to the scattering area in the wintertime. The solid curve corresponds to focusing to the waveguide center to the point at the depth of 36 m, the dashed curve corresponds to focusing to the sea bottom at the depth of 72 m. Circles indicate regions in the vicinity of the focusing point.

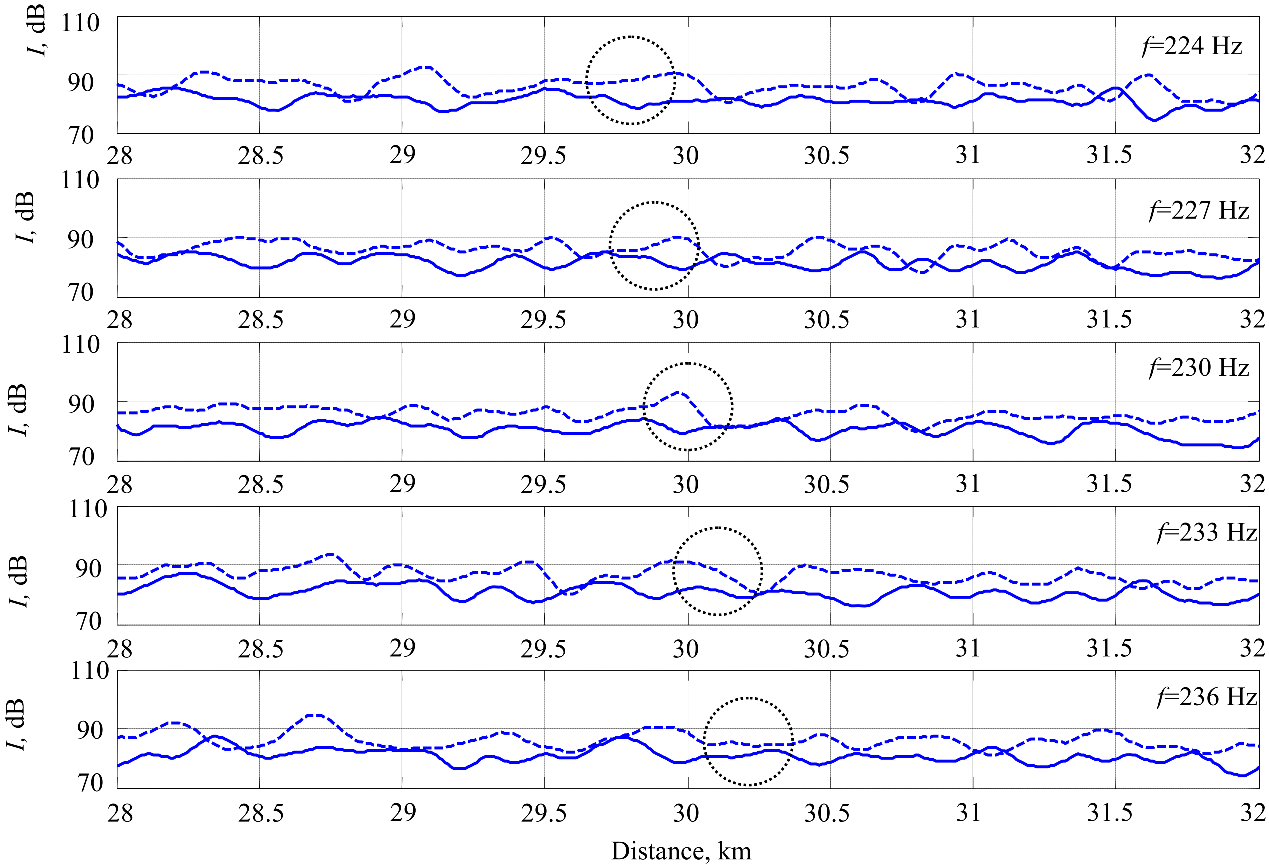

Fig.4. Dependence of the scattered field intensity on the distance to the scattering area in the summertime for intense internal waves. The solid curve corresponds to focusing to the waveguide center to the point at a depth of 36 m; the dashed curve corresponds to focusing to the sea bottom to the point at a depth of 72 m. Circles indicate regions in the vicinity of the focusing point.

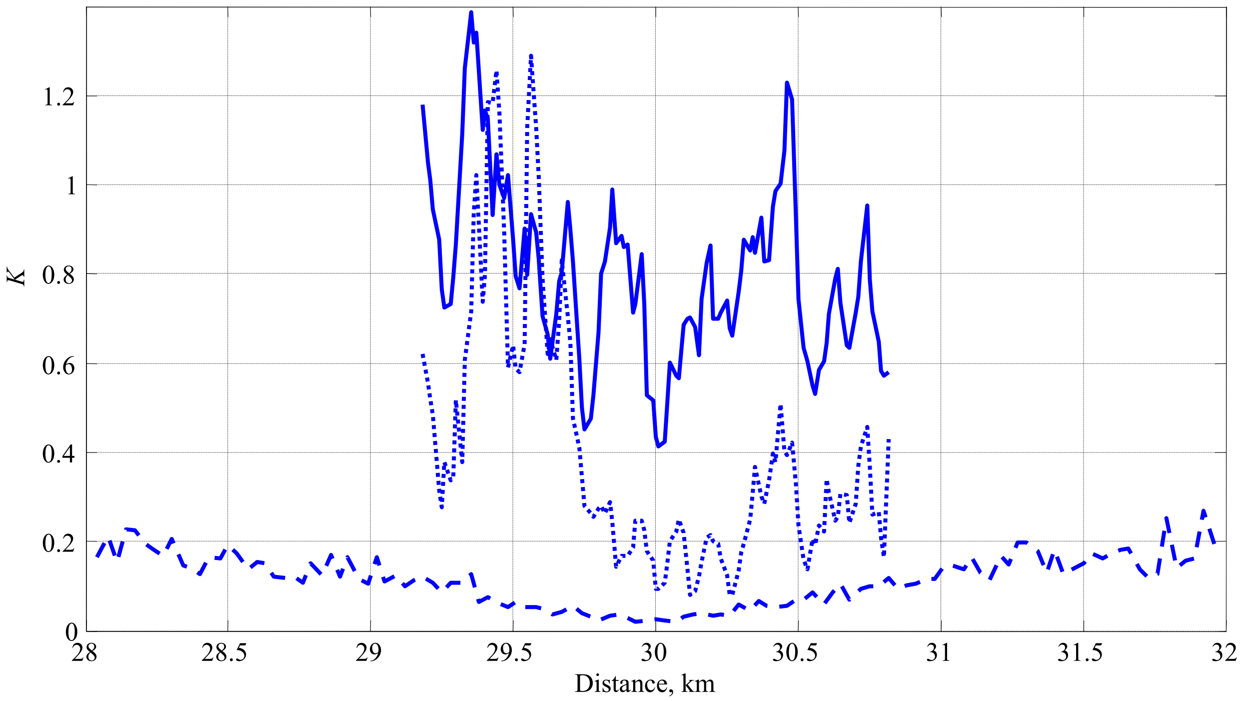

Fig.5. Ratio of magnitudes of scattered signals for focusing to the waveguide center and sea bottom. The dashed curve corresponds to wintertime hydrology, dotted and solid curves correspond to summertime hydrology without and with internal waves, respectively.

reverberation signal intensity maxima and minima. Here $|p_c^{sc}|$ and $|p_b^{sc}|$ are the average magnitudes for focusing to the center and bottom, respectively.

Fig.5 shows the dependence of K on the distance for the wintertime and the summertime without and with intense background internal waves. For wintertime hydrology, the ratio K remains rather small when the focal spot is displaced to one kilometer from the point of initial focusing. However, in the summertime, the distance range with a sufficiently small K becomes significantly narrower. In the waveguide with internal waves, it is impossible to control bottom reverberation (Fig.4) by focal-spot scanning in horizontal. Thus, in the waveguide with a constant sound speed over depth, bottom reverberation can be controlled in the widest distance range.

Acknowledgements

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