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Formation Characteristics of the Zonal Structure of Acoustic Fields in the Deep Part of the Sea of Japan

Formation Characteristics of the Zonal Structure of Acoustic Fields in the Deep Part of the Sea of Japan

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Abstract. The results of modeling the effects of stochastic levels of sound speed on formation of the zonal structure of acoustic fields for the hydrologic and acoustic environment of the deep part of the Sea of Japan. Numerical experiment involved calculation of the vertical structure of acoustic fields at the ranges from 20 to 120 km with discontinuity equal to 50 m in beam zooming for the set values of random component of sound speed field. In accordance with calculation, analytical correlations of changing coordinates of the closest and the furthest borderlines of the first three convergence zones at emitter depth depending on the level of random component of sound speed field were determined. Changes in borderlines of convergence zones occur in accordance with linear law; this said, the closest borderlines shift towards the emitter and the furthest borderlines – away from it. The obtained results of analyzing changes in structure of vertical distribution of acoustic field at the borderlines of convergence zones can be applied for engineering the systems of underwater monitoring for detection of local disruptions of acoustic velocity field of various nature against natural stochastic parameters of water environment in the deep part of the Sea of Japan.

1. Introduction

Zonal structure of an acoustic field is the interleaved sequence of zones of illumination and shade. It is formed with converging ray tracings and sound focus in convergence zones (CZ) due to refraction and outlet of acoustic beams that propagate in underwater waveguides to the surface. The outstretch of zones depends on the distance from emitter to the axis of underwater acoustic channel and changes with increase of sequential number of the zone – horizontal outstretch of convergence zones increases and the shade zones become smaller.

The results of experimental research of long-range acoustic propagation in the ocean significantly differs from the expected ones that were obtained via smooth profiles of sound speed. Illumination of the acoustic shade zone, the CZ shift, and an earlier arrival of acoustic beams are observed [1-4]. For instance, position of the closest borderline of the first convergence zone for the regions of the Indian Ocean, the Mediterranean Sea, the Sea of Japan and The Norwegian Sea show differences of experimentally obtained values from expected ones by 0,5-2,5 km [5]. Dependence of shift of the starting part of the first convergence zone towards the sound emitter on the depth in comparison with calculation data was observed in the Atlantic ocean (approximately by 2 km with receiving depth of 190 m and by 2.5–3 km with receiving depth of 880 m); moreover, there was a more significant shift of the second convergence zone in comparison to the first one – for the first zone of convergence it was approximately 3–3.5 km and 4–4.5 km – for the second one [3]. The difference between numerical mod-

eling and experimental data is usually explained with small-scale inconsistency of the sound speed due to temperature and salt-content fluctuations that must be taken into account when modeling acoustic propagation in the ocean [4,6,7].

This work presents results of modeling the influences of small-scale hydrological inhomogeneities on formation of zonal structure of acoustic field for hydrologic and acoustic environment of the deep part of the Sea of Japan in ray approximation. Numerical research of acoustic fields allows to predict correctly the key characteristics of received signals at the channels that are a few thousands of kilometers long. The results obtained via approximation the ray acoustics fairly correlate with both calculations via method of parabolic equation and data of natural experiments [8].

In calculative models of effects of small-scale hydrological inhomogeneities, the sound speed field is represented as

$$C(x,z) = C_0(x,z) + \Delta \tilde{C}(x,z) \, ,$$

where $C_0(x,z)$ – is the determined component of the acoustic velocity field, which generally smoothly depends on both coordinates, and $\Delta \tilde{C}(x,z)$ – is the random component; this said, $<\Delta \tilde{C}(x,z)>=0$, x, z – are the coordinates of range and depth accordingly.

2. Initial data of the numerical experiment

The research of the zonal structure of acoustic field was conducted based on numerical solution of the ray tracing equation in alternate field of sound speed that was obtained from the Fermat's principle. The Monte Carlo method was used for modeling the random component of sound speed field [9,10]. Research that was conducted earlier showed opportunity for determining stochastic level of the sound speed field for a particular region of the ocean through comparison of calculation results that were obtained via this given method of stochastic modeling of effects of small-scale inhomogeneities of sound speed on the acoustic field structure and these experiments for hydrologic environment of the Atlantic Ocean [11].

Zonal structure of the acoustic field in oceanic waveguide and the deep sea at various emitter depths significantly differs, which can be explained with difference of the axis depth of the underwater acoustic channel – for the deep sea it is about couple hundred meters and in oceanic waveguides – it is 1000 – 1500 m. Databases of the interdepartmental information system for accessing resources of marine information systems and complex information support of the marine activities were used as initial data (ESIMO) [12], scheme of the region and profile of the vertical profile of the sound speed are represented in Figure 1.

Initial data for the numerical modeling: polygon length – 120 km, emitter source is located higher than axis if the underwater acoustic channel at the depth of 50 m. The flare angle of the emitter is ±6°, which corresponds to the water propagation of ray tracings without multipath propagation from the seafloor and the surface for all selected values of the random component of the sound speed field. Discontinuity of output of ray tracings equals to 0.02°. The random component of the sound speed field $\tilde{C}(x, z)$ was discretely changing from 0 to 0.3 m/s with discontinuity equal to 0.01 m/s. For each value $\tilde{C}(x, z) > 0$ there were conducted 1000 experiments.

3. Results and discussion

The following results were obtained upon the conduct of the numerical experiments on determina-tion of changes of the closest and the furthest borderlines of the convergence zones at the emitter depth with regard to the level of random component. The closest borderlines of the convergence zone shift towards the emitter when the level of the random component increases and the furthest ones – away from it in accordance with linear law.
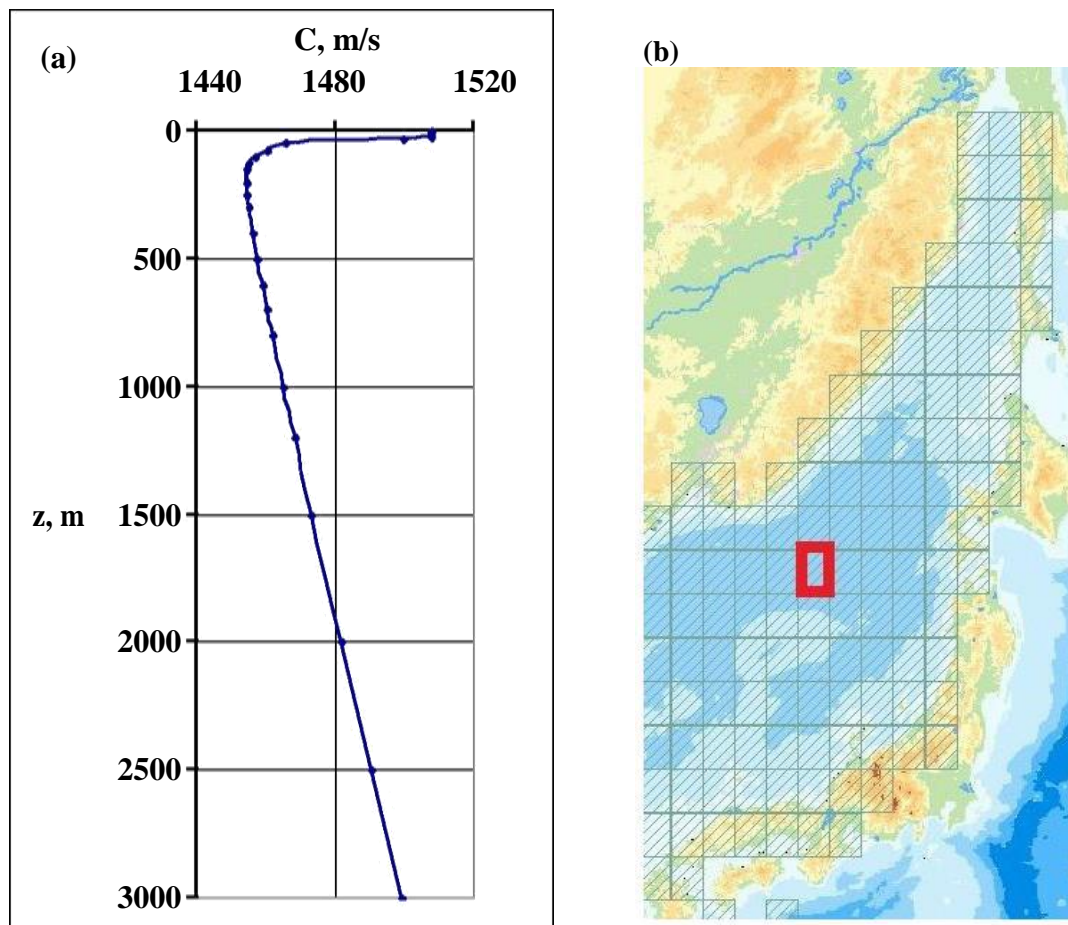
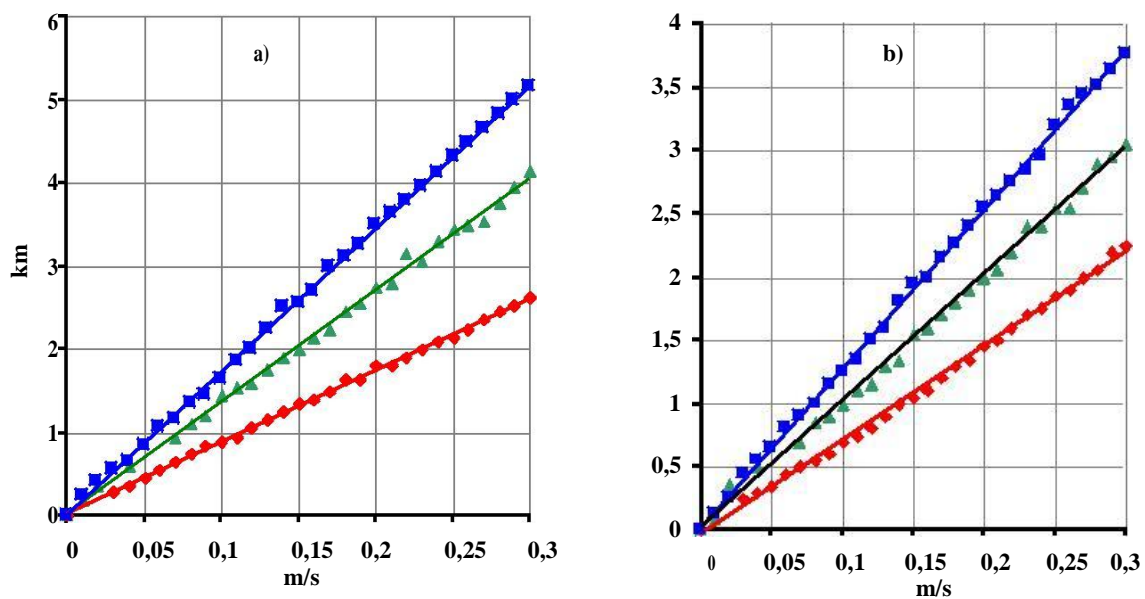**Figure 1**. Sound speed profile – a, region scheme – b [12].

Figure 2. Changes of the absolute delta of coordinates of the closest (a) and the furthest (b) borderlines of the first three convergence zones with regard to determined hydrology. Red color – the first convergence zone, green – the second convergence zone, blue – the third convergence zone.
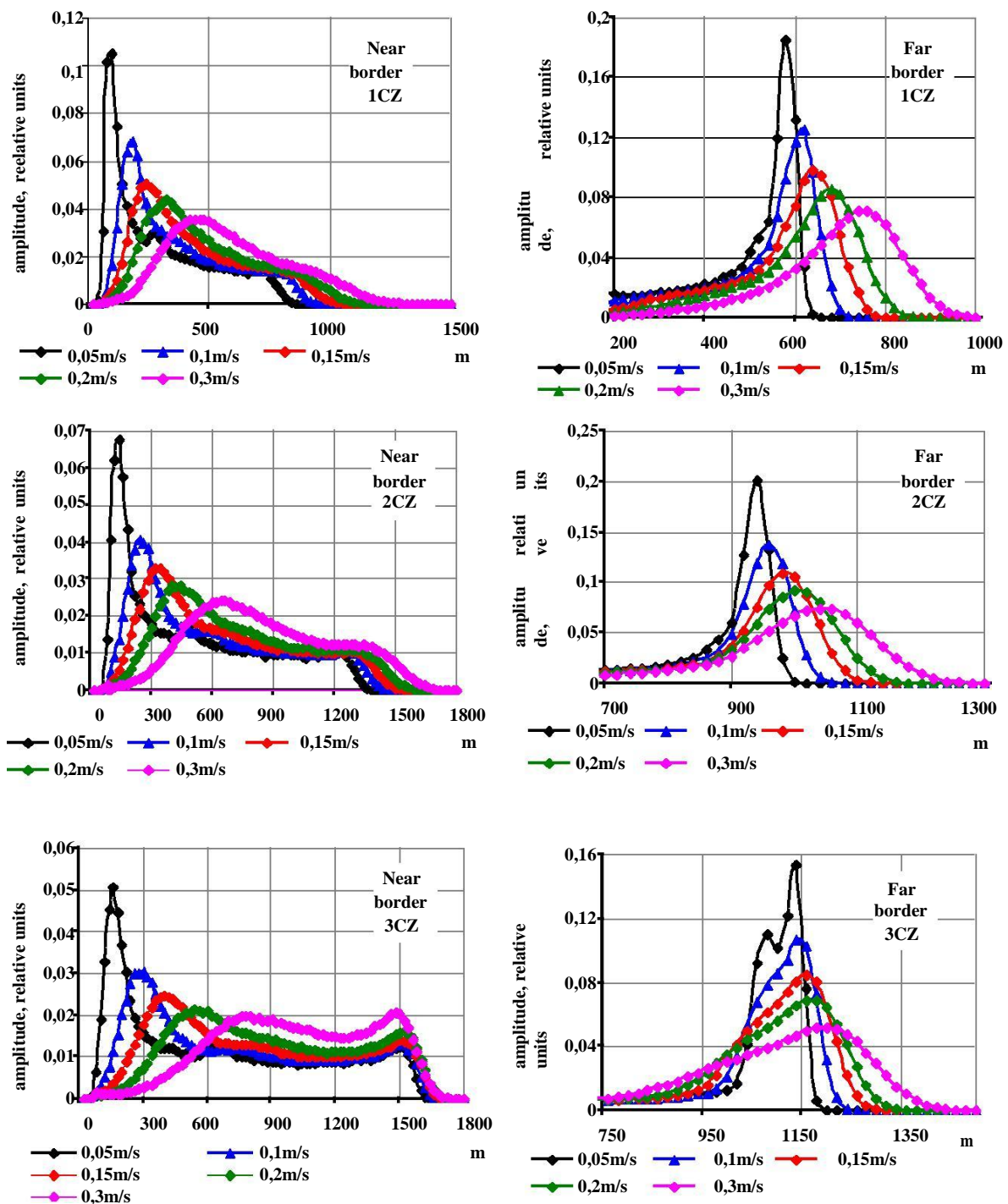
Figure 3. The vertical distribution of sound speed at the borderlines of the first three convergence zones. The x-axis represents depths of arrival of the ray tracings and the y-axis – is the amplitude of maximums of the acoustic field in relative units.

Figure 2 shows the correlations of changing the absolute delta of coordinates of the closest and the furthest borderlines of the first three convergence zones with regard to determined hydrology. The y-

axis covers values of the level of the random component of the sound speed field and the x-axis – the absolute delta of coordinates of the convergence zone borderlines at emitter depth.

Based on correlations in Figure 2 it can be concluded that with set values of the level of the random component of sound speed field, the coordinates of the closest borderlines of the convergence zones shift towards the emitter at a longer distance then the furthest ones shift away from the emitter. This said, the higher the sequential number of the convergence zone, the stronger shift of the closest and the furthest borderline coordinates occurs.

Figure 3 shows the correlations of changes of the vertical distribution of acoustic field at the closest and the furthest borderlines of the first three convergence zones depending on the level of random component of the sound speed field. As it follows from the presented materials, vertical distribution of the acoustic field have one distinct maximum; with increase in the level of the random component of the sound speed field from 0 to 0.3 m/s, the amplitudes of maximums decrease and their coordinates by depth shift sideways in accordance with linear law (see Table 1).

Table 1. Analytical correlations of shifts of the maximum vertical distribution of acoustic field by depth at the CZ borderlines depending on the random component of sound speed.

	The closest borderline	The furthest borderline
The first convergence zone	z = 1258,6bk + 57 m	z = 682,7bk + 546,4m
The second convergence zone	z = 2021,7bk + 37,6m	z = 411,4bk + 921m
The third convergence zone	z = 2598bk + 29,6m	z = 269,7bk + 1119m

In Table 1, z – is the coordinate of depth of the maximum vertical propagation of sound speed field, b – is the value of the random component of sound speed field, k – is the size coefficient. As it follows from the presented materials, with increase of the sequential number of the convergence zone, the speed of coordinate shifting of the maximum vertical distribution of sound speed by depth at the closest borderlines increases and at the furthest ones – decreases. This said, the coordinates of depths of the maximum vertical distribution of acoustic field at the closest borderlines shift faster than at the furthest ones. Analytical correlations presented in Table 1 are determined via standard MS Excel functions with approximation accuracy equal to $R^2 \geq 0,97$.

4. Conclusion
The results of the numerical experiments on the effects of the random component level of the sound speed field on the zonal structure of acoustic fields in the deep part of the Sea of Japan can be used for the development of experimental and theoretical methods of zoning the aquatoriums by the stochastic level of the water environment and choosing the optimal locations for the underwater monitoring systems that are based on methods of illuminative hydrology.

5. References
[1]   Van Uffelen L J, Worcester P F, Dzieciuch M A and Rudnick D L 2009 The vertical structure of shadow-zone arrivals at long range in the ocean *JASA* **125 (6)** pp 3569-88

[2]   Galkin O P, Kharchenko E A and Shvachko L V 2000 Acoustic field structure in the first oceanic convergence zone for different frequencies in the audio range *Acoustical Physics* **46 (3)** pp 274-283

[3]   Galkin O P and Shvachko L V 2003 Investigation of the sound field structure in the ocean with a deep-water reception *Acoustical Physics* **49 (6)** pp 653-661

[4]   Van Uffelen L J, Worcester P F, Dzieciuch M A, Rudnick D L, and Colosi J A 2010 Effects of upper ocean sound-speed structure on deep acoustic shadow-zone arrivals at 500- and 1000-km range *JASA* **127** pp 2169–81

[5]   Vadov R A 2005 On the predictability of the positions of the convergence zones in the ocean *Acoustical Physics* **51 (3)** pp 265-270

[6]   Galkin O P, Gostev V S, Popov O E, Shvachko L V and Shvachko R F 2006 Illumination of the

shadow zone in a two-channel oceanic waveguide with a fine structure of sound speed inhomogeneities *Acoustical Physics* **52 (3)** pp 252-258

[7] Virovlyansky A L, Kazarova A Y and Lyubavin L Y 2012 Focusing of sound pulses using the time reversal technique on 100-km paths in a deep sea *Acoustical Physics* **58 (6)** pp 678-686

[8] Virovlyansky A L 2005 Statistical description of ray chaos in an underwater acoustic waveguide *Acoustical Physics* **51 (1)** pp 71-80

[9] Kirianov A V, Salnikova E N, Salnikov B A and Slesarev N Yu 2015 Modeling and study of main regularities of the formation of sound fields in randomly inhomogeneous underwater waveguides *Proc. of Meetings on Acoustics* **24** Issue **1** *5th Pacific Rim Underwater Acoustics Conf.: PRUAC 2015* 23 September 2015 Vladivostok

[10] Salnikov B A and Salnikova E N 2008 Modeling and study of the zonal structure of acoustic fields in randomly inhomogeneous underwater waveguides *Underwater studies and robotics / FEB RAS Scientific & Technical Journal* (Vladivostok: Dalnauka) pp 47-57

[11] Kirianov A V 2018 The effect of the small-scale variability of sound velocityon the zonal structure of acoustic fields in oceanic waveguides *The Far Eastern Federal University: School of Engineering Bulletin* Issue **2** pp 64-70

[12] Interdepartmental information system for access to the resources of marine information systems and integrated information support for marine activities URL: http://portal.esimo.ru