Regional Variability of Influence of Small-Scale Sound-Speed Fluctuation Levels on the Acoustic Fields Formation in the Ocean

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Abstract. The results presented herein are the research findings about the influence of small-scale inhomogeneity’s in water environment on the structure of acoustic fields for hydrological and acoustical conditions that are typical for the Atlantic and Pacific Oceans. Small-scale sound-speed fluctuations were modeled by adding a stochastic perturbation to the deterministic mean profile. Quantitative experiment was conducted to determine the dynamics of changes in the first three convergence zones at the depths of emission source in relation to the random componentry in the sound-speed field. Analytical dependences of increasing widths of upper convergence zones on the level of the random componentry in the sound-speed field were determined based on the results of quantitative experiment. With increasing stochasticity levels, the width of convergence zones increases in accordance with linear law, and the absolute increments grow with the increase of convergence zone number. When the values of a random componentry in the sound-speed field are fixed, the absolute increment of width of the upper convergence zones in the Atlantic Ocean is higher than in the Pacific Ocean. This said, the gradient of a smooth profile of the sound velocity by depth above the axis of hydroacoustic channel is higher in the Atlantic Ocean. Consequently, the absolute increments of width of the convergence zones depend not only on the levels of stochasticity parameters of water environment, yet, also, on the gradient size of smooth profile of the sound speed at depths above the axis of hydroacoustic channel.

1. Introduction
During the conduct of experiments on the research of angular and energetic structure of acoustic field in the ocean, a significant difference between experimental data and computations that involve the smooth profile of the sound velocity is observed. The shift of convergence zones towards the emission source is observed [1,2]. This said, the bigger the difference, the higher the convergence zone number. Thus, for [2] the hydrological conditions of the Atlantic ocean, with the closest borderline of the first convergence zone at the receiving horizon of 190 m and emitter depth of 200 m, the shift was around 2 km, whereas at the depth of underwater hydroacoustic channel of about 880 m, the shift was 2.5-3 km.

The reason behind differences in results of quantitative modeling and experimental data are the small-scale inhomogeneity’s of sound speed, which are represented with sharp anisotropic formations that are caused by fluctuations of temperatures and salinity of water environment. Horizontal scales of the acoustic fluctuations are, usually, 10 – 100 times larger than the vertical ones [3]. The influence of small-scale inhomogeneities shows itself in registration of acoustic fields in the shade zones; there are
differences in arrival time of rays and depth of their fixation from the computed values when using the smooth profile of sound speed [4,5]. Lately, there are attempts of considering the small-scale inhomogeneities that are based on stochastic models and intended as a solution for problems of acoustic tomography [6].

During works with methods of stochastic modeling, the influence of smooth profile of sound speed on the first four convergence zones in the Pacific and Atlantic Oceans was researched with regards to dependence on the random componentry level for the acoustic propagation field (or the fixed values for the random componentry level for the acoustic propagation field).

For the account of small-scale inhomogeneities during the conduct of quantitative experiments, the sound-speed field is described as two additive components: the determined one and the random one, which is suitable for describing via statistical methods [7]. In typical waveguide models this function is represented as follows [8]:

\[ C(x,z) = C_0(x,z) + \Delta C^r(x,z), \]  

where \( C_0(x,z) \) — the deterministic mean profile, which is, in general, smoothly depending on both coordinates, and \( \Delta C^r(x,z) \) — the random componentry, with \( \langle \Delta C^r(x,z) \rangle = 0 \). In the theory of wave propagation in stochastic environments, the description of rays is based on the use of the term of statistical ensemble of environmental implementations [9]. Statistical characteristics of a ray with set parameters of \( z_0 \) and \( \phi_0 \) — the initial depth and output angle from emitter accordingly — are determined via averaging by the rays with same initial conditions in various environmental implementations, which create the ensemble. This approach to the analysis of stochastic ray-structure of the field is borrowed from radiophysics and is based on the physical model of ray pipes [3, 10, 11]. The model of ray pipes implies that fluctuations of acoustic velocity lead to the random wandering of ray tracings with regard to an undisturbed ray; thus, a ray pipe forms within space and consists of a beam of rays with close propagation paths. With minor fluctuations the ray tracings do not intersect and with major ones — the do, which implies various methods of computing the structures of acoustic fields in the randomly-stochastic underwater waveguides. Nevertheless, this approach does not consider refraction as the main mechanism of acoustic field formation at long ranges.

2. Choice of the mathematical model of the problem

Studying the zonal structure of acoustic fields on the basis of quantitative solutions for the equation of ray tracings in a variable acoustic velocity field, which is derived from the Fermat's principle, – is the alternative to analytical solving methods for the stochastic waveguide equation [12,13]. This approach allows estimation of pattern distortion in acoustic fields from a unified position and under any stochastic mode of hydrophysical parameters of a waveguide (weak, strong and intense fluctuations of an sound-speed field).

The equation of ray tracings in a variable sound-speed field that is derived from the Fermat's principle is as follows

\[ C(x,z) \cdot \frac{d^2z}{dx^2} - \left( 1 + \left( \frac{dz}{dx} \right)^2 \right) \left( \frac{dz}{dx} \cdot \frac{\partial C(x,z)}{\partial x} - \frac{\partial C(x,z)}{\partial z} \right) = 0, \]  

where the general model of sound speed \( C(x,z) \) is described with the equation (1).

The Monte Carlo method was used for modeling the environmental stochasticity. Anisotropic stochasticity of waveguide parameters was modeled via accounting the random componentry of the sound-speed field. The modeling polygon is divided into rectangular units; via a random number generator the maximum values \( \Delta C^r(x,z) \) are distributed in the unit centers and the values do not exceed fixed values. The assigned value \( \Delta C^r(x,z) \) decreases to zero by the unit borders.

The results of quantitative experiment were processed by the averaging method “by depth”. The averaging method “by depth” implies averaging the modeling results by discrete depth intervals \( \Delta z \) of incoming ray tracings to the vertical profile at fixed range. Unlike the method of ray pipes, the
averaging method “by depth” allows consideration of all rays that came to the selected averaging interval Δz, including the ones that have different initial conditions – the rays that were emitted from the source under different angles. This approach allows studying the acoustic field structure within the unified mathematical model, as well as determination of main influential patterns for the random componentry of sound speed at any stochastic level.

Discrete by range, the vertical profiles of an acoustic field (VPAF) \( P(x,z_n) \) adequately describe its zonal structure:

\[
P(x,z_n) = \frac{L_n(x)}{L \cdot m},
\]

where \( L_n(x) \) – the number of rays that came to the \( n \)-interval of depth of the vertical profile, which is located at the \( x \)-distance from the emitter over the \( m \)-experiments; \( L \) – the number of rays that were emitted from the source during one experiment; \( m \) – the number of experiments conducted. This standardization is one of the modifications of the consistent field method, with

\[
\sum_{n=1}^{N} P(x,z_n) = 1,
\]

where \( N = H/\Delta z \) – is the number of equidistant discrete readings of VPAF, \( H \) – the sea depth at the vertical profile location, \( \Delta z \) – the interval of averaging an acoustic filed by depth, \( n \) – the number of discrete reading by depth (the discrete coordinate of depth), \( z_n = \Delta z \cdot n \) – the current depth coordinate. In this case the discrete function \( P(x,z_n) \) can be interpreted as the depth probability distribution for ray tracings at the fixed range \( x \).

The suggested processing algorithm for stochastic modeling represents the development of calculation methods for acoustic fields and is based on building an extensive ray picture without calculations of an acoustic field amplitude at the ray [14].

In our case, the procedure of computing the averaged field \( P(x,z_n) \) at discrete readings of depth \( n \) comes to simple toting of rays that intersect \( n \)-interval of depth \( \Delta z \) fixed at \( x \)-range, without computing their focal factor. This approach, unlike the classic ray method, allows accurate computation of an averaged field at the points of ray bends and at caustics.

3. Description of the numerical experiment

Quantitative modeling was conducted for the hydrological conditions of the Caribbean region of the Atlantic Ocean [2] and the canonical Mank profile [15,16], which is the most typical for the conditions of the Pacific Ocean [17]. Computer software program was used for the conduct of quantitative experiment [18]. Smooth profiles of sound speed that were used for the quantitative experiment are represented in fig. 1.

The initial data for the quantitative modeling was selected as follows: polygon length – 240 km, the emitting source is located at the depth of 200 m. The angle of source opening is ±8°, with output discretization of ray tracings equal to 0.05°, which corresponded to the water distribution of ray tracings without rereflecting from the ocean floor and surface – for all selected values of the random componentry of the sound-speed field. For the purposes of modeling small-scale inhomogeneities, the polygon was divided into rectangular units 25 m in depth and 500 m in range. The random componentry of the acoustic velocity field \( \Delta C \approx (x,z) \) discretely varied from 0.05 to 0.45 m/s. A thousand (1000) of experiments was conducted for each value \( \Delta C \approx (x,z) \). The vertical distribution of an acoustic field was computed within the ranges from 40 to 240 km with discretization equal to 500 m; the 10 m interval of depth averaging for ray tracings was selected.
4. Results and discussion
The results of modeling are shown in fig. 2. With increase of stochastic levels, the width of convergence zones increases in accordance with linear law, whereas the absolute increments grow with the number of a convergence zone. This is caused by the fact that with the increase of range, the amplitude of random deviations of ray tracings from the undisturbed ray increases; this also includes refraction. With increase of level of the random componentry of the sound-speed field, the nearby borderlines of convergence zones shift closer to the emitter, whereas the remote ones – shift from the emitter. This is explained with the fact that the rays, which form the close borderlines of the convergence zones, propagate from sea floor to the surface, and the flaring of shade zones occurs; this applies to the shade zones at the top of the depth range for the incoming ray tracings that is “allowed” by the smooth acoustic velocity profile. The remote borderlines of convergence zones are formed with rays that propagate from the sea surface to the floor. Downward flaring of shade zones occurs; therefore, the coordinates of convergence zones shift towards increasing.

5. Conclusions
The results of quantitative experiments show dependence of absolute increments of the width of convergence zones on the hydrological conditions of the World Ocean. According to our opinion, there is dependence not only on the stochastic levels of water environment parameters, yet on the type of smooth profile of sound velocity as well (see fig. 1). The absolute increments of the width of convergence zones at fixed values of the random componentry for the acoustic velocity field in the Atlantic Ocean are larger than in the Pacific Ocean. This can be explained with the larger gradient of the smooth profile of sound speed above the axis of underwater acoustic channel in the Atlantic Ocean. Consequently, when all other conditions are equal, the absolute increments of the width of
convergence zones depend not only on the level of the random componentry for the sound-speed field, yet on the gradient value of the smooth profile of sound speed above the axis of underwater acoustic channel as well.

![Figure 2](image_url)

Figure 2. Absolute increments of convergence zones: (a) the first convergence zone, (b) the second convergence zone, (c) the third convergence zone. 1 – the Pacific ocean, 2 – the Atlantic ocean. Analytical dependencies of absolute increments of width of the upper convergence zones on the level of random componentry of the sound-speed field are shown in the figure. The x-axis represents the stochasticity level of the sound-speed field, the y-axis – the absolute increments of width of the upper convergence zones at the depth of emitting source.

6. References

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