Reliable data on the fine structure of the sound field at long and extra-long distances in underwater waveguides are still of high priority in ocean acoustics. These data are required to understand the physical meaning of the processes that occur in the ocean and to solve certain engineering problems. To that end, the main task is to establish the predominant features of the sound field (in appropriate frequency bands), which determine the stable field structure governed by the deterministic ocean inhomogeneities, and the irregular field components governed by random ones. Starting from the 1950s, the author of this paper developed methods for studying sound field structure on the basis of separating and identifying the field components in methods for studying sound field structure on the basis of separating and identifying the field components governed by random ones. The role of the channel inhomogeneities in the violation of the sound field coherence is determined for different frequency bands. On the basis of the experimental data, the vertical distribution of the critical frequencies of the waveguide is obtained, and the validity limits are established for the wave and ray calculation methods. The applicability of the phase methods for calculating the sound fields in waveguides with dispersion is discussed. The frequency–angular dependence of the effective sound attenuation coefficient in an underwater waveguide is revealed and explained. © 2002 MAIK “Nauka/Interperiodica”.

This paper considers the space–time structure of the sound field and the power “capacity” of the underwater sound channel in certain frequency bands (a 1/3-octave filter is used). We also study the “geometric” dispersion of the sound speed in the underwater channel and the degeneration of the refraction ability of the channel, consider the phase stability of the wave fronts in the waveguide with dispersion, analyze the conditions of the formation of normal waves in a real underwater channel, study the origin and mechanisms for the regular field components to lose their coherence as functions of frequency and range, experimentally determine the critical frequencies for different waveguides and the frequency limits of validity for the ray computation technique along with the limits for using the intensity summation to calculate the sound field in a waveguide with dispersion, and reveal and explain the frequency–angular dependence of the effective attenuation coefficient for an underwater sound channel.

The experiments were performed in the central region of the Black Sea on a path 600 km in length. The path was oriented in the latitudinal direction at an angle of 285° relative to the receiving vessel with a sea depth of 200 m. The hydrological environment was rather steady along the path. The sound speed profile showed a stable underwater sound channel with its axis at the depths 30–50 m and a weakly pronounced surface channel of 5–20 m in thickness. The measured sound speed profiles along the path are presented in Fig. 1. The sea state was Beaufort 1–3. The research vessels drifted at the reception and transmission points. The
distance between the vessels was determined by navigational means and recalculated from the measured propagation times of the sound signals. As the sound sources, explosive charges (120 pieces weighing 2.5 kg each) were used. The charges exploded at depths of 10–80 m and at distances of 150, 300, and 600 km. The signals were received by omnidirectional hydrophones at depths of 10, 35, 50, and 80 m. The signals were analyzed at frequencies ranging from 1 Hz to 5 kHz.

To analyze the space–time and power–frequency structures of the sound field and the dispersion properties of the waveguide, let us consider a low-frequency broadband record obtained at a distance of 600 km. The typical shape of the explosion-generated signal received near the channel axis is shown in Fig. 2 for 35-m and 50-m depths of explosion and reception, respectively. The abscissa axis represents the running time, with a linear scale of the signal amplitude on the ordinate axis. The record contains frequencies ranging from 1 to 300 Hz. In the figure, vertical lines are the time marks separated by 100 ms.

The sets of the received signal components corresponding to the ray quartets for the low and infralow sound frequencies are produced by the shock wave and by two oscillations of the gas bubble. The sets are formed purely by water rays: there are no surface and bottom reflections. At the beginning of the record, separate regular components of two sets can be noticed that are generated by the shock wave (signals 1, 2, 3, …) and first oscillation (signals 1′, 2′, 3′, …) with a period of 125 ms. The components produced by the second oscillation have levels which are lower by 10–15 dB than that of the shock wave; they are masked by the latter and weakly pronounced in the record. The signal elongation in the broad band, which is governed by the high-frequency components, is 4.95 s (5.2 s in view of the oscillations). The differences in the delay times are 250, 240, 200, … ms for the initial regular components. For subsequent components, these differences decrease and tend to zero in the limit.

The received sound pressure as a function of time can be associated with a quasi-sinusoidal function that represents the geometric dispersion of the sound speed in the channel. The quasiperiod of this function is equal to the doubled difference in arrival times of the signals in the quartets of rays, for which the number of cycles differs by one. The measured levels of separate components, which are governed by the focusing factors, change by 3–4 dB. In the domain of fully-developed dispersion (the frequencies 40–300 Hz), the general signal level increases by less than 2–3 dB because of the in-phase summation of the regular components. At high frequencies, the characteristic angles (i.e., the angles at which the channel axis is crossed) are within the range ±14° for the rays captured by the waveguide. In the low-frequency band, this angular range strongly depends on the frequency and tends to zero at the critical frequency of the entire waveguide.

Fig. 1. Vertical profiles of the sound speed along the experimental path at the distances (1) 0, (2) 150, (3) 300, and (4) 600 km in the Black Sea.

At the beginning of the record, separate components that are caused by the shock wave are graphically compared with the quasi-sinusoid corresponding to the lowest frequencies of the refracted waves. For the components to be summed nearly in phase and for the dispersion to be well pronounced in the low-frequency spectrum, it is required that the distance be much longer than 600 km. According to the critical frequency of the entire waveguide, the distance must be sufficient to provide equal differences in the arrival times of the first and second, as well as the second and third, signal quartets, which is the condition that can be met nowhere but