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Horizontal Refraction of Acoustic Signals in the Shelf Area and a Coastal Wedge of the Black Sea

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Abstract—Results are presented from an experimental study of the propagation of acoustic pulses on the shallow marine shelf of the Black Sea and a coastal wedge. Signals associated with bathymetric refraction are analyzed. Short-period signal fluctuations on a Black Sea coastal wedge along stationary acoustic tracks with a mean bottom slope of ~25° are studied. The spectra and characteristic periods of fluctuations in the amplitude, azimuthal angles, angles of slide, and arrival times of pulsed signals are determined. The main reasons for fluctuations in the characteristics of signals under conditions of pronounced horizontal refraction with changing bathymetric characteristics are discussed.

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INTRODUCTION

The ocean shelf is characterized by a gentle mean slope of the bottom (usually no more than 1°). In some coastal areas, however, the slope of the bottom can be quite steep (units and tens of degrees). In ocean acoustics, features of the propagation of sound in relatively shallow waters with a sloping bottom with multiple reflections from the seabed are studied using the model of a so-called coastal wedge. The possibility of horizontal sound refraction in a coastal wedge became clear immediately after the discovery of an underwater sound channel and the construction of a theory of wave propagation in a layered medium [1]. Systematic studies of this phenomenon have recently become relevant, however, due to the development of new approaches to acoustic sounding of the shelf sea. In modern hydroacoustics, no problem of the acoustic sounding of a coastal wedge is considered without the contribution from horizontal refraction. The problem of studying the horizontal refraction of acoustic emission propagating in an inhomogeneous ocean is one of acoustic imaging of the ocean's structure to study and monitor it [2]. Researchers who this investigate this phenomenon focus on the shelf zone [3], where tides and internal waves are strong [4, 5]. The variability of the parameters of the ocean waveguide in the horizontal plane as a result of changes in bathymetry or the speed of sound propagation results in the horizontal refraction of acoustic waves. These effects have been studied theoretically and experimentally for both the deep ocean [6] and the shelf sea [7, 8]. It has been shown that there are numerous acoustic manifestations of horizontal refraction in a coastal wedge. The first measurements of horizontal angles of arrival in a coastal wedge were made in [9]. The focusing and defocusing of a sound field in the horizontal plane with internal waves was studied next in [10]. The horizontal multipath effect, changes in the interference pattern in the horizontal plane of a coastal wedge [11] or in a submarine canyon [12], and other phenomena have also been studied. The importance of horizontal refraction in solving inverse problems was also discussed in [13, 14]. We recently confirmed that pronounced horizontal refraction is possible in a coastal wedge of the Black Sea off the coast of Abkhazia, along the Cape Sukhumsky–Cape Kodor track [15]. In other words, no problem of the acoustic sounding of a coastal wedge is considered without the contribution from horizontal refraction.

In this work, we present the results from an experimental study of recording acoustic pulses in the shelf area of the Black Sea in both a shallow coastal wedge near the town of Gelendzhik and on a steep shoreface in the waters off Cape Sukhumsky. Signals associated

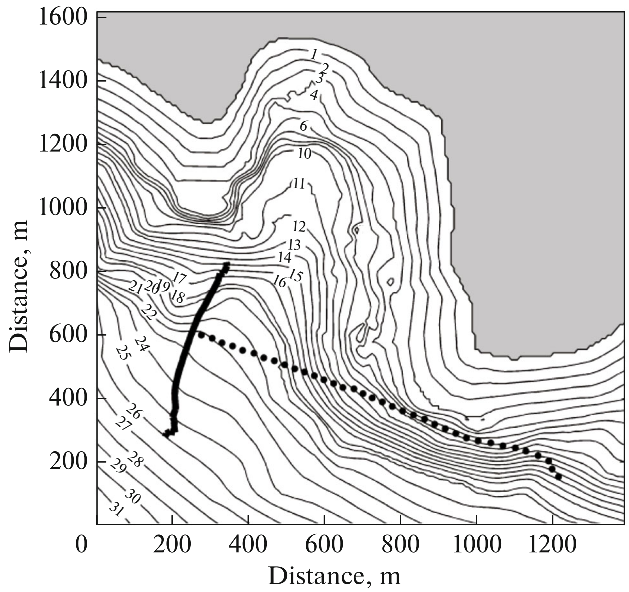

Fig. 1. Bathymetry of the water area. The heavy line indicates the position of the antenna. Dots show the places where signals were emitted on one tow.

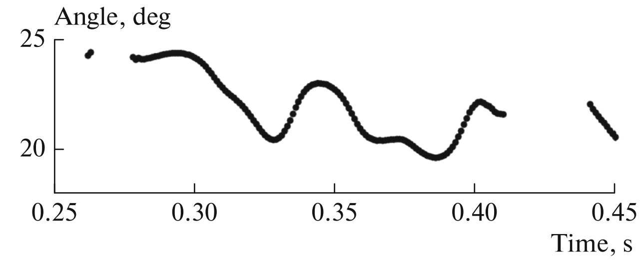

Fig. 2. Change in the angle of arrival for a pair of receivers of the seabed antenna (nos. 42 and 43).

with bathymetric refraction are analyzed, and the main reasons for fluctuations in signal characteristics under conditions of pronounced horizontal refraction are discussed.

REFRACTION OF SOUND IN A SHALLOW COASTAL WEDGE

Aspects of recording acoustic pulses with a long seabed antenna in a shallow coastal wedge in the shelf area of the Black Sea were studied experimentally near Gelendzhik in the waters of Blue Bay. A seabed antenna in the form of a chain of 50 receivers positioned roughly across the isobaths (Fig. 1) was used to receive the sound signals. Receiver no. 1 was located at a depth of around 14 m; receiver no. 25, at a depth of 23 m; and receiver no. 50, at a depth of 26 m. The distance between the receivers was kept constant (12.5 m). The coordinates of the antenna receivers were determined from their location using a special technique. An pneumatic gun towed parallel and perpendicular to the antennas at depths of 2.5–3 m was used to emit acoustic signals. The pneumatic gun emitted short acoustic pulses every 20 s as it was towed

The signal source's maximum distance from the antenna was 1037 m. The position of the source during an emission was determined via GPS. The energy of the pneumatic gun's emissions was mainly in the range of 10–500 Hz. The speed of sound's profile with a minimum at the bottom resulted in the propagation of sound with multiple reflections from the seabed. The duration of signals recorded at distances of more than 300–400 m was at least 0.15 s (much longer than that of the emitted signals), which corresponded to multipath propagation. The angle of a wave's arrival in the horizontal plane (azimuth) was determined by correlating the signals received by a pair of neighboring receivers. To do so, we first determined the delay in a signal's time of arrival between pairs of receivers using cross-correlation analysis. We then determined the azimuth of a wave's arrival using the model of a homogeneous medium and small slide angles (Fig. 2).

Figure 2 shows that the angle of arrival varies over a signal's duration by around 5° at a distance of 390 m from the emitter. The individual arrivals that make up the signal thus do not propagate along a straight line connecting the source of the sound to the receiver in the horizontal plane, but along arcs with different lengths. The nonmonotonic nature of this change was apparently due to the angle of arrival being affected not only by horizontal refraction but by a change in the slide angle as well, which was impossible to control in our experiment. Such features of the propagation of acoustic signals are explained by calculating the ray paths according to the program in [16] for the digital model of relief and profile of the speed of sound corresponding to the experimental conditions (Fig. 3). We can see that at slide angles greater than 8°, the antenna barely intersects with direct rays from the source at a distance of about 1 km. This corresponds to the very weak signals observed in the experiment at distances from 500 to 1000 m.

REFRACTION OF SOUND ON A STEEP SHOREFACE

Our experiments were performed in the waters of the Black Sea range of the Abkhazia Academy of Sciences' Institute of Ecology near Cape Sukhumsky. The slope of the seabed at a distance from the coast was approximately 23°–25°. Mounted on a metal rod, the receiving system was lowered from an oceanographic platform to a depth of 6 m (the depth at that location was 12.6 m). The receiving system consisted of three hydrophones positioned in the horizontal plane on an equilateral triangle with sides 1 m long. This system allowed us to determine both the azimuth and the slide angle of signal at a known speed of sound

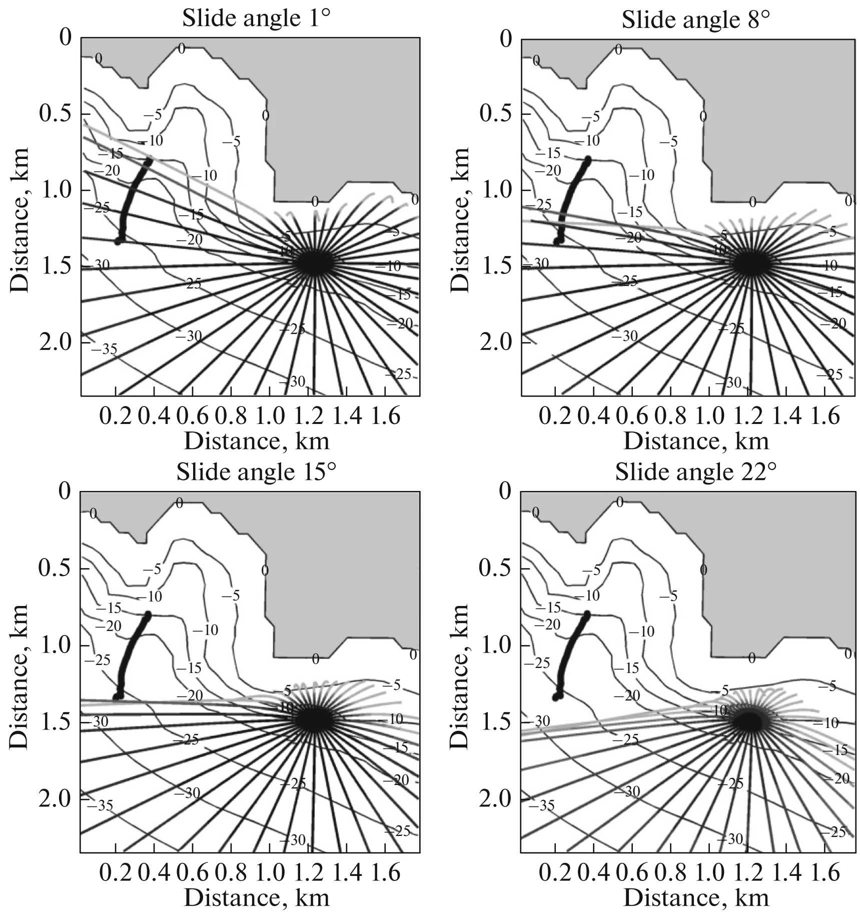

Fig. 3. Projections of ray paths on the horizontal plane with different slide angles. The transition from black to gray trajectories corresponds to the reduction in the intensity of sound.

propagation from the delay between signals arriving at different receivers. Two emitters positioned at a distance of 0.4 m from the seabed were used in our experiment (see Fig. 1). The first emitter (E1) was located at a distance of 133 m from the receiving system, a depth of around 72 m, and an azimuth of approximately 176°. The second emitter (E2) was located at a distance of 81 m from the receiving system (RS), a depth of around 10 m, and an azimuth of approximately 71°. The main difference between the location of the emitters was that the line connecting E1 and RS was almost perpendicular to the isobaths, while the one connecting E2 and RS was almost parallel to isobaths along the coast. This positioning of the emitters allowed us to compare the main features of signal propagation under conditions of strong and negligible bathymetric refraction. Direct signals without reflections from the seabed and surface must in both cases be quite stable in their parameters. Signals from source E2 with reflections from the sloping bottom must be highly susceptible to bathymetric refraction, since not only the slide angle changes with such an orientation of the acoustic track but the direction of propagation in the horizontal plane as well. The larger the slide angle, the greater the number of reflections from the bottom, and the stronger the change in the direction of propagation in the horizontal plane. Signals from source E2 propagating with different slide angles must arrive at the receiving point from different azimuths. The signals from source E1 propagating with different slide angles perpendicular to the isobaths with reflections from the sloping bottom are not terribly susceptible to bathymetric refraction and will arrive at the receiving point from an azimuth close to the true azimuth of the source. The speed of sound profile is shown in Fig. 3b.

Signals with linear frequency modulation were emitted in the 3–8 kHz band and lasted for 0.004 s. The maximum width of the correlation function of the emitted signal was approximately twice the inverse value of the band (i.e., approximately 0.0004 s). Considering the nonuniformity of the frequency characteristics of the emitters and the influence of the medium of propagation, we would expect some expansion of the correlation maximum, but the arrival of individual signals with intervals of more than 0.001 s must be resolved. To increase the temporal resolution of

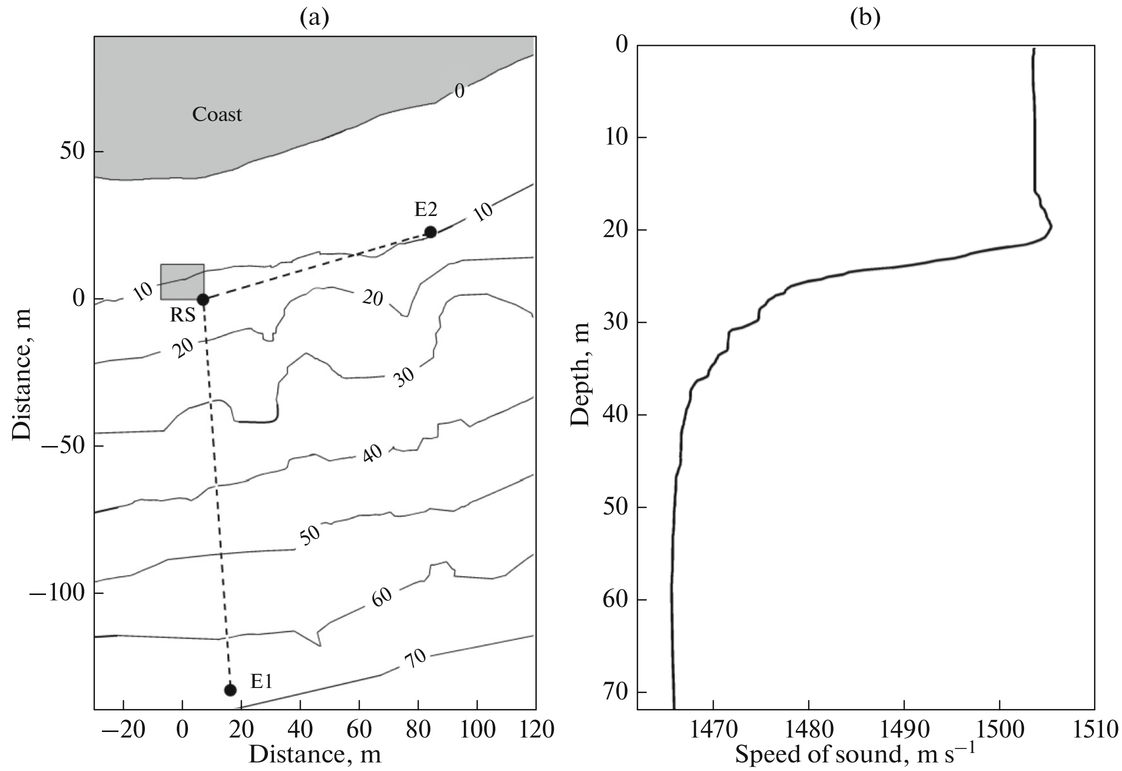

Fig. 4. (a) Bathymetric chart. RS is our three-element receiving system; E1 and E2 are the emitters. (b) Profile of the speed of sound.

individual arrivals when measuring azimuths and slide angles, we determined the pulse characteristics of the hydroacoustic channel by calculating the cross-correlation function of signals received and emitted for each receiver. Each series of measurements consisted of 100 pulses followed at intervals of 1 s.

Figure 4 presents the two-dimensional pattern of the temporal variation of the envelope of the cross-correlation function of the received and emitted signals. Note that the signal from the second emitter is longer and has considerably more arrivals.

Figure 5 presents the results from measuring azimuths and slide angles for signals from sources E1 and E2. Note that the signal from source E1 consists of two arrivals (pulses) with azimuths of 176.5° and 178.5° (which are close to the true azimuth to source E1) and very different slide angles of 22.5° and 34.5°. However, the signal from source E2 has a characteristic sign of bathymetric refraction: as the slide angle grows, the azimuth of signal arrival narrows substantially (i.e., it shifts toward the coast). This change in the azimuth of arrival is important. For the first direct signal propagating without reflections from the seabed and surface (since the speed of sound propagation is virtually constant up to a depth of 15 m (Fig. 1)), an azimuth of 70.5° is close to the true azimuth to the source E2. For subsequent arrivals, the azimuth narrows to 69.5°, then to 65.5°–56.5°, then to 63.5°–57.5°, and finally to 49.5°–41.5°. The observed maximum deviation from the true azimuth to the source is thus close to 29°.

CONCLUSIONS

The propagation of acoustic waves in the shelf sea in areas with a complex topography of the seabed must be considered as a three-dimensional problem of underwater sound propagation. If the sea's surface and bottom form a narrowing wedge, acoustic rays rise along it and repeatedly reflect from the surface and the sloping bottom. A ray deviates slightly toward the steepest slope as it reflects off the bottom. In other words, we can see the ray's path is curved if we observe the process from above, and refraction occurs in the horizontal plane. We studied this process for two typical cases (under the conditions of both the shallow shelf near Gelendzhik and the steep shoreface in the area of Cape Sukhumsky).

The shelf sea was studied using a long bottom antenna, allowing us to determine the azimuth of an acoustic signal's arrival with a high degree of accuracy. Refraction on the steep shoreface in the area of Cape Sukhumsky was studied using a three-element receiving system. At a sufficient signal-to-noise ratio, this system can determine both the azimuth and the slide angle of an incoming signal if the speed of sound is known.

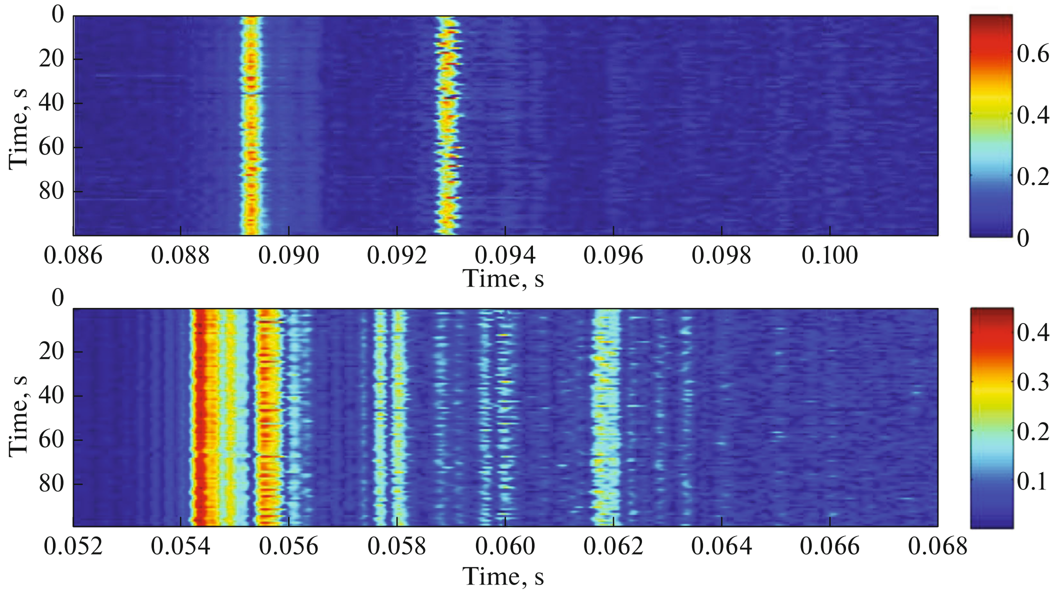

Fig. 5. Temporal variation of the envelope of cross-correlation function for received and emitted signals for E1 (top) and E2 (bottom). The time of emission is plotted along the ordinate axis; the time of signal arrival, along the abscissa axis. Colored scales show the values of the coefficient of cross correlation.

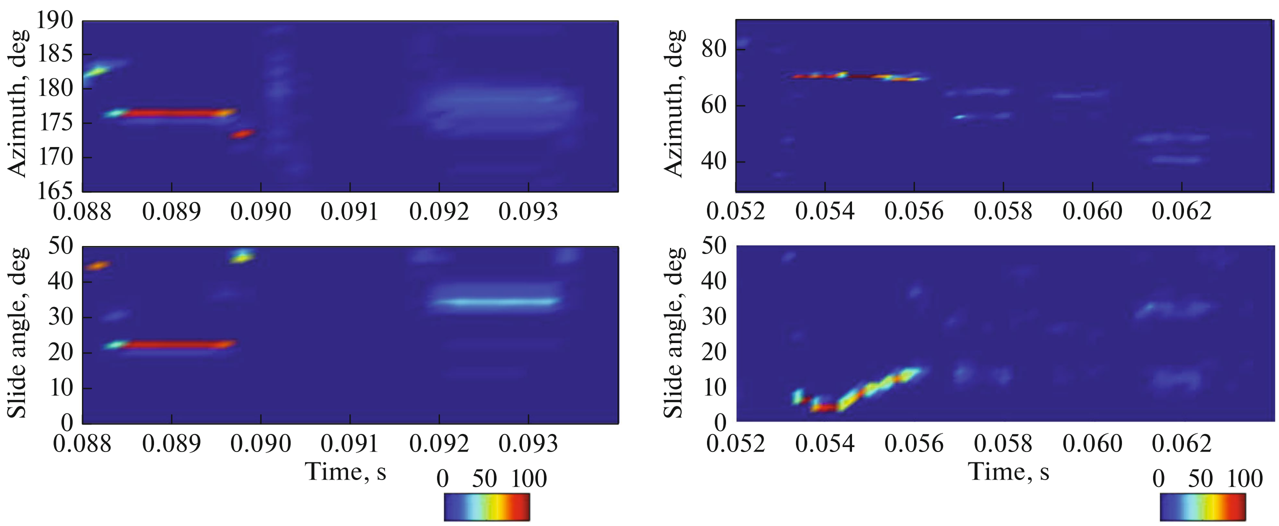

Fig. 6. Results from measuring the azimuths and slide angles for signals from sources E1 (left) and E2 (right). Color scales show the number of pulses out of 100 in a series falling in the interval of 1° in azimuth and 2° in the slide angle for the time of a given signal (time step, 0.00001 s).

We found that the azimuth of arrival changes with the duration of the signal recorded by the antenna. The end of a signal is formed by rays resulting from bathymetric refraction in a different direction than at the beginning of the signal. The signal propagates along an arc from the emitter to the antenna receivers. This behavior of the acoustic signal corresponds to the results from calculating the ray paths for the experimental conditions. Experiments show that at slide angles greater than 8°, the antenna barely intersects with direct rays from the source at distances of around 1 km. This corresponds to the very weak signals observed at distances of 500 to 1000 m.

The relationship between the azimuth and slide angle of an acoustic signal arriving at the receiving system was found using a three-element receiving system in experiments on the steep shoreface in the waters off Cape Sukhumsky. Under these conditions, the observed deviation of the azimuth from the true azimuth to the source was 29° when the slide angle to 30°.

It is especially worth noting that the development of techniques and programs for calculating sound propagation in three-dimensionally inhomogeneous media is required to solve practical problems of hydroacoustics and reliably interpret the results from experiments in coastal waters. This will allow the modeling of complex seabed topography and changing fields of flow and the speed of sound.

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