# PROPAGATION OF PULSED SOUND SIGNALS ON A SHELF OF FREE TIDAL SEA: EFFECTS FROM COASTAL EDDIES AND INTERNAL WAVES

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*A long-term experiment on studying fluctuations of the parameters of pulsed sound signals in a shallow sea was carried out in the region of the northeastern coast of the Black Sea in autumn, 2004. The data were collected on a 1.2-km fixed propagation path at a 2-km distance from the coastline. During the entire experimentation, observations of temperature fluctuations near the receiving point were performed by the using the line temperature sensor. Fluctuations of the shape, energy, and propagation time of the pulsed signals were studied. An attempt of their relation to the hydrodynamic processes on the shelf was taken. The change in the shape and the energy level of the signals was analyzed for the moment of passing the anticyclonic topographic eddy over the coastal zone. It was shown that the fluctuations of the propagation time were sometimes as high as 17.6 ms. An enhance of the short-period acoustic fluctuations accompanying the intensification of the internal waves was observed.*

## INTRODUCTION

The coastal zone of seas and oceans is that of the highest dynamical variability of the medium characteristics because it is just where the most intense interaction between the sea, atmosphere, and land takes place. In view of the importance of this zone for the economic activities, environmental control, and frontier defense, the monitoring of the coastal regions is urgent for more clearly understanding the processes that occur there.

In recent years, Andreyev Acoustics Institute regularly performs experimental studies in the coastal zone of the northeastern part of the Black Sea, in summer and autumn seasons [1]. The studies are carried out at the experimental site of the Southern Division of Shirshov Institute of Oceanology, RAS, in the Blue Bay near Gelendgik. The main objectives of the experiments consist in studying different aspects of monitoring the sea medium and the hydrophysical variability in the coastal region. In this paper, we present the data of the sea experiment that was performed in October, 2004.

## 1. EXPERIMENTAL TECHNIQUE

The experiment consisted in long-term acoustic and hydrophysical measurements on a fixed 1.2-km propagation path that was oriented approximately in parallel to the coastline, along the 30-m isobath. The transmitting and receiving systems were at nearly 2-km distance from the coast. They were mounted on bottom-moored tripods. The heights of the transmitter and receiver above the bottom were 0.9 and 1.4 m, respectively. From October 2 to 10, 12 records of pulsed signals were obtained, 30 min to 9 hrs in their duration. The carrier frequency was 2300 Hz, the duration of the pulses was $1.5 \cdot 10^{-3}$ s. The width of the spectrum was 930 Hz (2300 ± 465 Hz) at the -3 dB-level. The transmitted pulses were separated by 4 s in time. The received signals and those feeding the transmitter were continuously two-channel recorded in a digital form. Such a manner of recording allowed us to measure the absolute time of propagation in signal processing.

In the experiment, the shape, energy, and the propagation time of the pulsed signals were analyzed, and an attempt was taken to relate these parameters to the hydrodynamical processes identified by direct measurements of the medium parameters.

The line temperature sensor was mounted at the reception point. The data obtained with it were continuously recorded during the entire experimentation. The sensor covered the near-bottom layer of 3 m in thickness, with its lower and upper ends at 1 and 4 m from the bottom, respectively, and measured the mean water temperature. Prior to the beginning of the experiment (September 29), two times during the acoustic measurements (October 4 and 8), and after the experiment (October 16), vertical profiles of the temperature and salinity were measured in the region of experimenting. In addition, 6 in-sea passages, 3 to 5 hrs in their duration, were performed to survey the space distribution of the currents on the path, with the use of the RIO GRANDE 600 kHz acoustic Doppler current profiler (ADCP).

## 2. MAIN FEATURES OF THE HYDROLOGICAL AND METEOROLOGICAL PARAMETERS

The Black Sea, as a closed basin, is nearly free from tides and, hence, from the tidal internal waves, these processes being a strong factor of internal mixing in the ocean. With this regard, the main factors that govern the dynamics of currents and the structure of the water bulk in the Black Sea are the wind regime and the existence of coastal topographic eddies [2]. In the experiments of October 2 to 10, the sea state substantially varied, from dead calm to as strong wind as 17 m/s. The calm weather (October 2 to 4) changed into a period of wind waves (October 5) caused by eastern winds that persisted up to October 8. On October 10 to 11, the wind again became stronger, from the south in this case. The southern and eastern winds afforded the pileup of warm waters into the coastal zone. The passages with the ADCP on October 2 to 4 revealed an intense southeastern current along the coastline. This current reached its maximum (up to 0.4 m/s) on October 3, this fact being caused by an anticyclonic eddy that propagated on the shelf in the northwestern direction. During next three days, there were no surveys of the currents because of strong winds. On October 8, a current with the fully reversed northwestern direction was observed, this being an indication of the absence of the eddy.

Figure 1 shows the sound speed profiles, *c(z)*, that illustrate the stratifications that are typical for the experimental path. At the initial third of the experiment, a sharp stratification with the discontinuity layer was observed. Such conditions are illustrated by the profile of October 4. The discontinuity layer was lifted by the coastal anticyclonic eddy that was earlier (September 29) in near-bottom position. With the southeastern winds, the process of pileup began. This process led to water mixing, cooling in the upper bulk of the sea, and warming in the near-bottom layers. Simultaneously, the discontinuity layer returned to its near-bottom position (see profile of October 8).

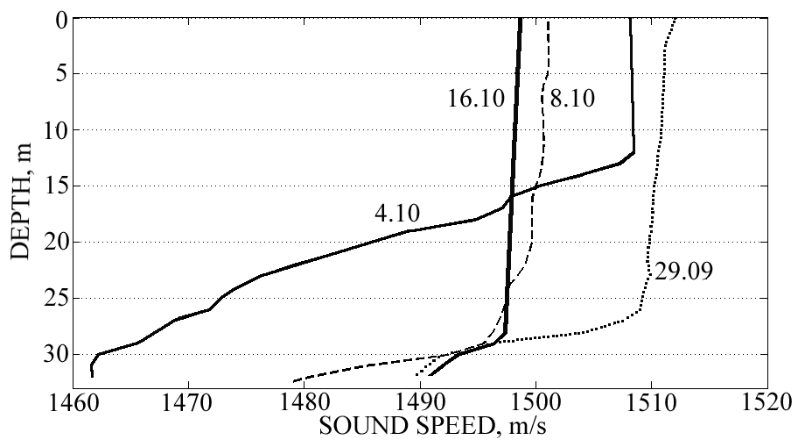


Fig.1 Typical sound speed profiles observed on September 29 and October 4, 8, and 16 on the path

Let us now consider the record obtained with the line temperature sensor (Fig. 2). The mean temperature of the near-bottom layer was initially rather low. It was a period (October 2 to 5) of passing the anticyclonic eddy when the cold water entered the near-bottom layer.

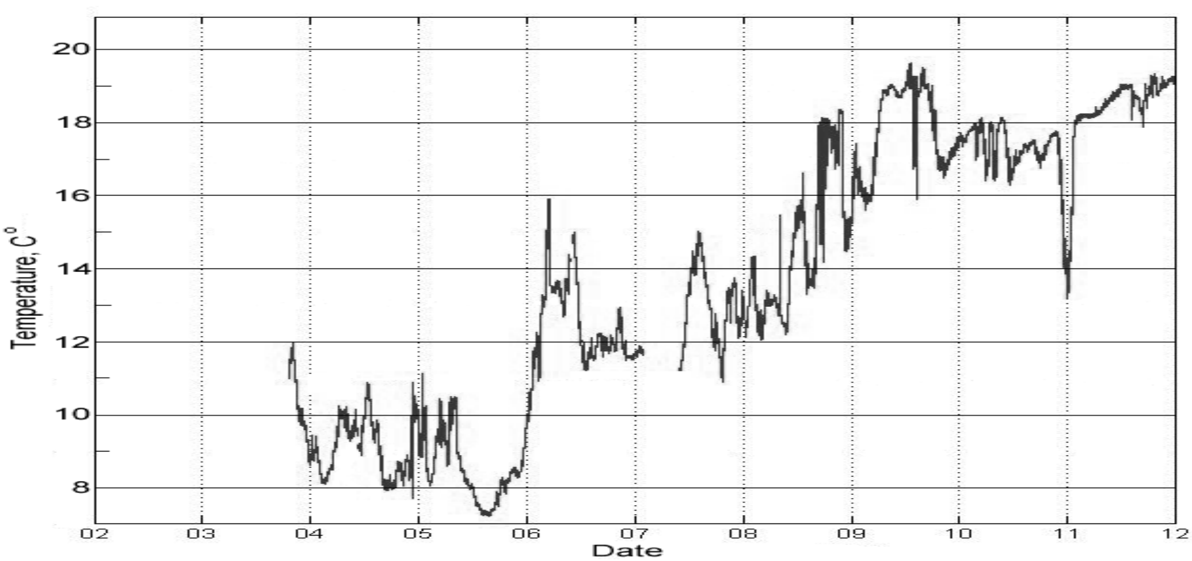


Fig.2 Data obtained with the line temperature sensor: the mean temperature of the near-bottom layer on October 3 to 12

The sharp warming of the near-bottom layer at night of October 5 to 6 was caused by the pileup of warm waters under the influence of strong eastern winds. In the next days, up to the end of experimenting, a trend of warming in the near-bottom waters is clearly noticeable. Such a trend is caused by the persisting pileup winds that made the thermocline being closer to the bottom. In addition to the long-period changes in the temperature, the record exhibits high-frequency oscillations with periods of several minutes to several tens of minutes. Such oscillations can be attributed to the influence of internal waves.

## 3. INFLUENCE OF THE COASTAL EDDY

Figure 3 shows the typical shapes of the signals for each of 12 records obtained in the experiment. On the right, the variation of the water temperature during experimentation is shown. All the observed differences in the propagation time and energy level of the signals are mainly caused by the changes in the position of thermocline and by continuously cooling the subsurface isothermic water layer – by more than 5°C during experimentation.

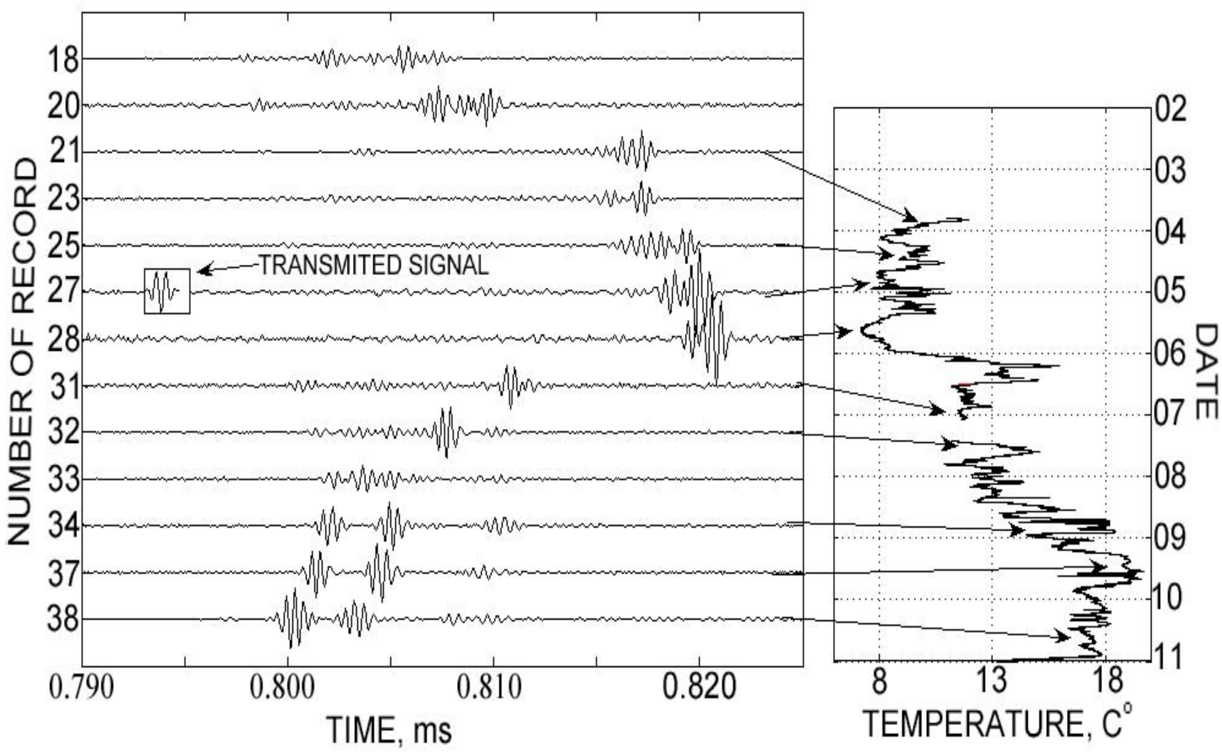


Fig.3 Shapes of the signals received at different moments of the experiment and variations of water temperature in the near-bottom layer at the reception point

The eddy-caused income of the near-bottom cold waters into the coastal area led to a substantial lifting of the thermocline, and, as a result, to a wide well-developed near-bottom sound channel that captured the main part of the acoustic energy (the upper part of Fig. 4 presents the ray pattern calculated for the eddy present on the path). In this situation, the energy of the signal is mainly contributed by the modes of lower numbers with minimal group velocities. The total signal consists of a compact group of pulses nearly unresolved in time (records nos. 27 and 28). After the passage of the anticyclonic eddy, the width of the near-bottom channel significantly decreases, and the sound energy occurs evenly spread over the entire water layer (the lower part of Fig. 4). At that time, the modes of lower numbers begin strongly interact with

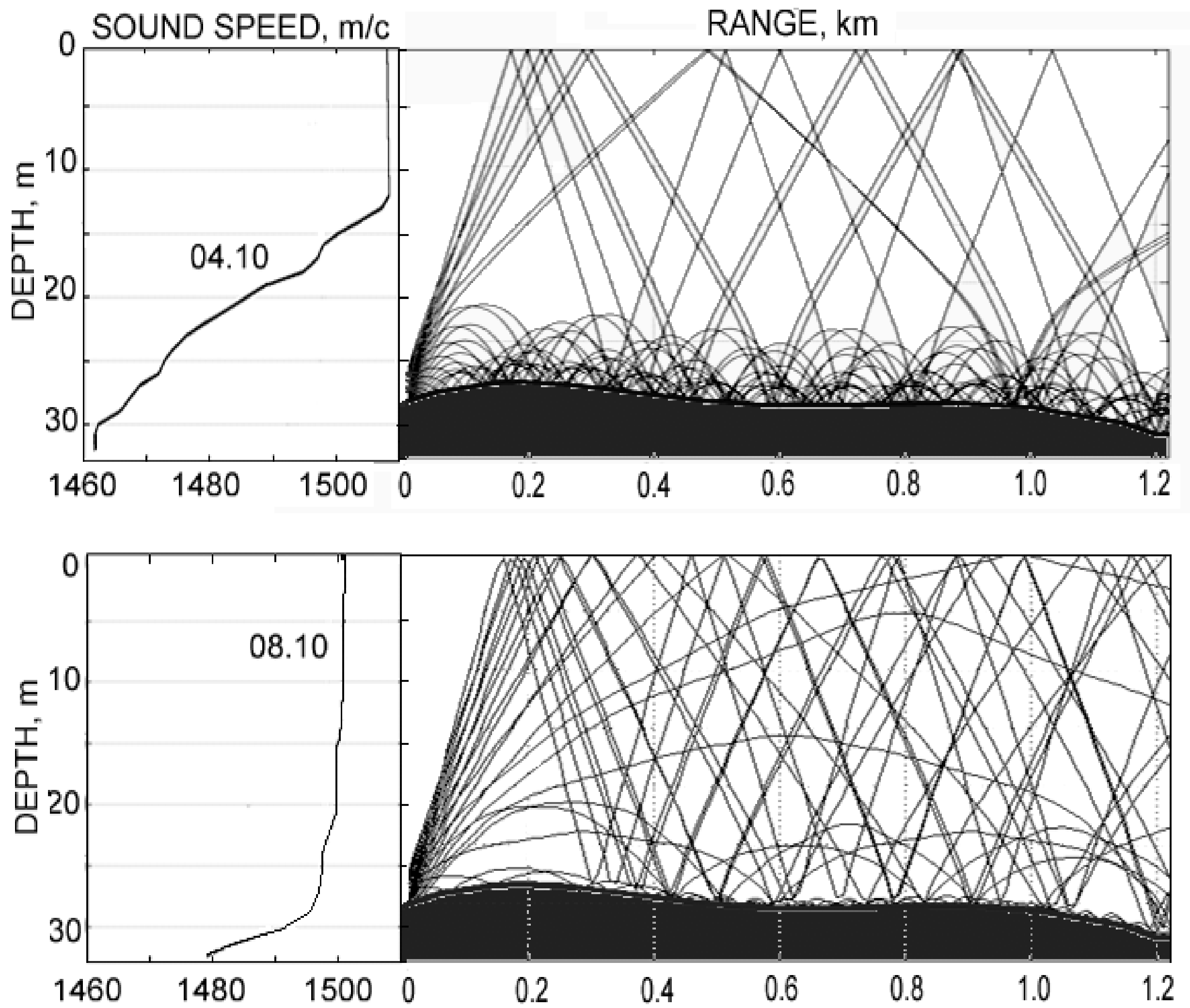


Fig.4 Ray patterns calculated for the typical vertical profiles of the sound speed on the path (the upper and lower patterns correspond to the absence and presence of the eddy). The bottom relief and the positions of the transmitter and receiver are also shown

the bottom, and their amplitude substantially decrease. Therefore, the signal energy is now mainly contributed by the modes of higher numbers that have larger group velocities and form the beginning of the signal (records nos. 18, 20, 34, 37, and 38). Figure 5 shows the intensity of the sound field calculated for the two aforementioned positions of the discontinuity layer, with and without the eddy.

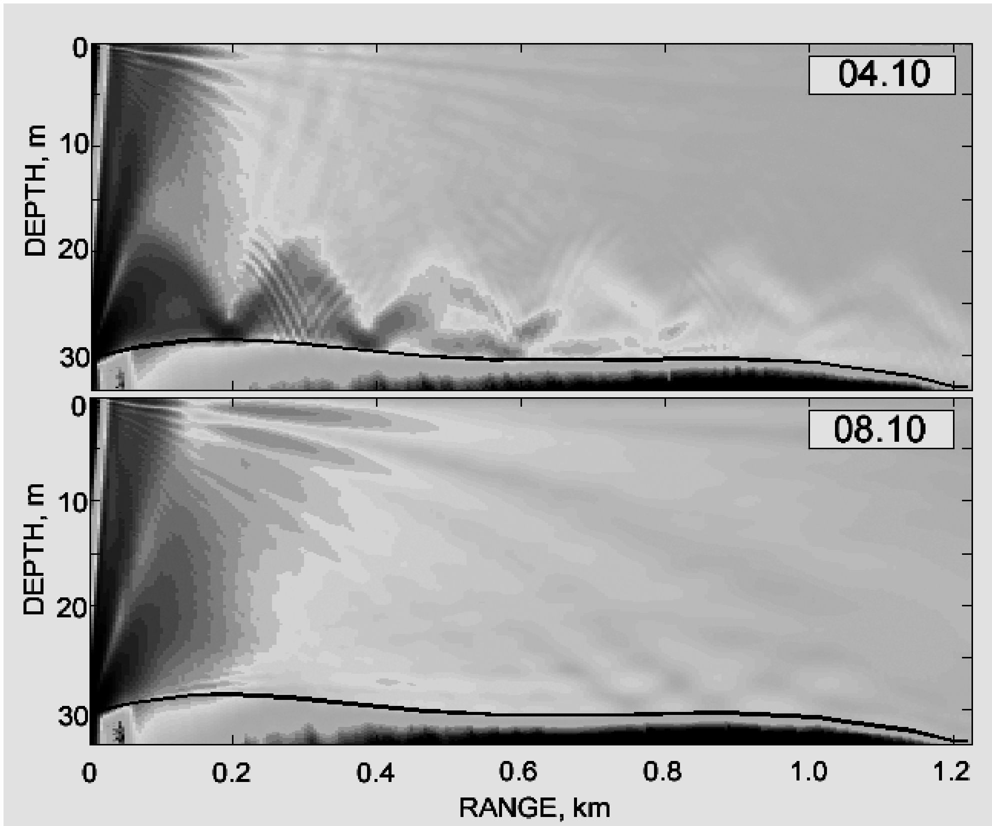


Fig.5 Distribution of the sound field intensity along the path for two sound speed profiles

## 4. EFFECTS OF INTERNAL WAVES

Figure 6 shows time dependences of the energy of the received signals and the temperature in the near-bottom water layer for the record no. 31. The energy of the pulsed signals was determined by numerically integrating the squared acoustic pressure over a fixed time interval whose boundaries were chosen in view of the maximal and minimal absolute times of signal propagation.

It is naturally to assume that the observed oscillations of the temperature (up to 1.5$^o$C) were caused by the passage of short-period internal waves. The second half of the record is free from the oscillations of the near-bottom temperature. This phenomenon can be attributed to the escape of the thermocline from the near-bottom area that was covered by the line temperature sensor. Nevertheless, the lifting of the thermocline caused substantial fluctuations of the signal energy.

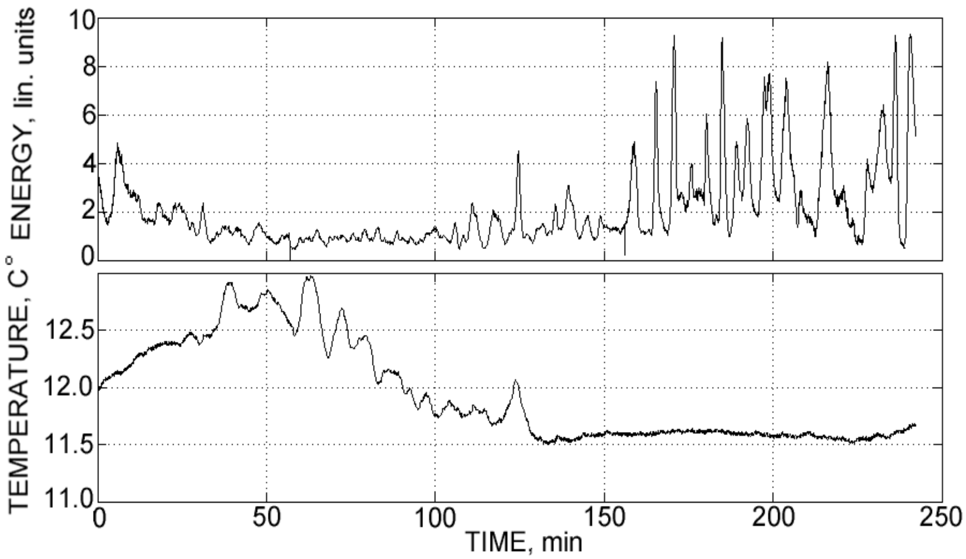


Fig.6 Energy of the pulsed signals (record no. 31) and temperature in the near-bottom water layer

The comparison of energy fluctuations for the signals in the first and second halves of the record (Figs. 6 and 7) indicates a substantial increase in the fluctuations for periods of 1.5 to 8 min. Such a frequency band is typical for short-period internal waves in the Black Sea.

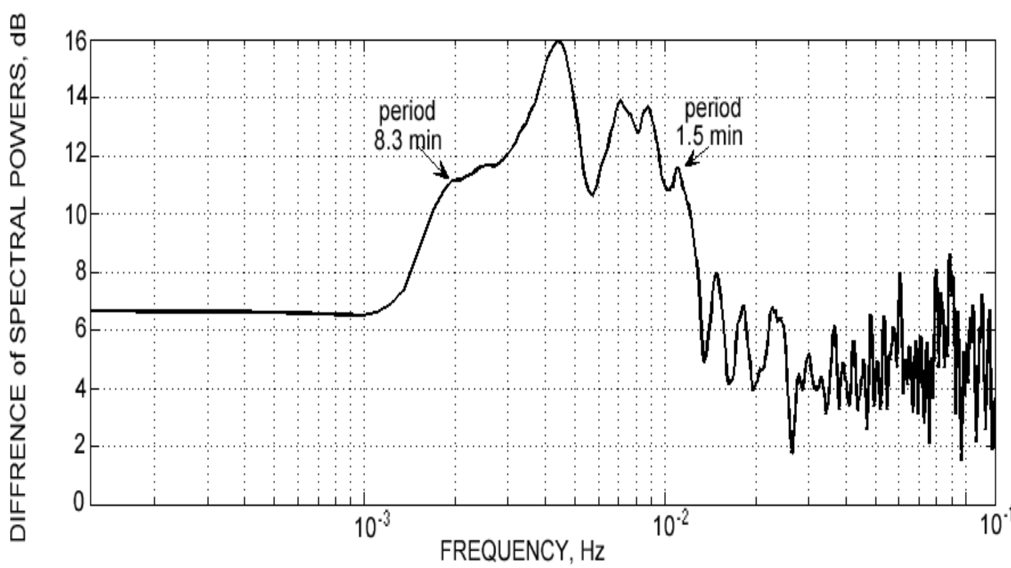


Fig.7 Difference in power spectra of the signals for the first and second halves of record no. 31

The large energy fluctuations shown in Fig. 6 exhibit smooth and nearly symmetric increase and decrease in the signal energy from minimal to maximal its values. However, the shape of the signal generally remains unchanged. To clear up the mechanisms of such variations of the signal energy, we computed the parameters of the signals when the propagation pass is crossed by trains of internal waves. In doing so, the computer code of Avilov [3] based on the pseudo-differential parabolic equation (the wide-angle approximation) was used.

On October 2, the ADCP measurements revealed the existence of a train of intense short-period internal waves on the path (Fig. 8). The internal wave with the maximal amplitude in the train had the following parameters: a height of 6 m, a length of 78 m, and a velocity of 0.19 m/s. According to the backscattering pattern, the synchronism of the oscillations caused by the internal waves is well noticeable through the entire sea depth. Such a synchronism evidences that the oscillations can be attributed to the first mode. The train was crossed twice, on the direct and reverse tacks (in the opposite and same directions, respectively), these two crossings allowing us to estimate the velocity of the internal wave. On the basis of the obtained data on the wave

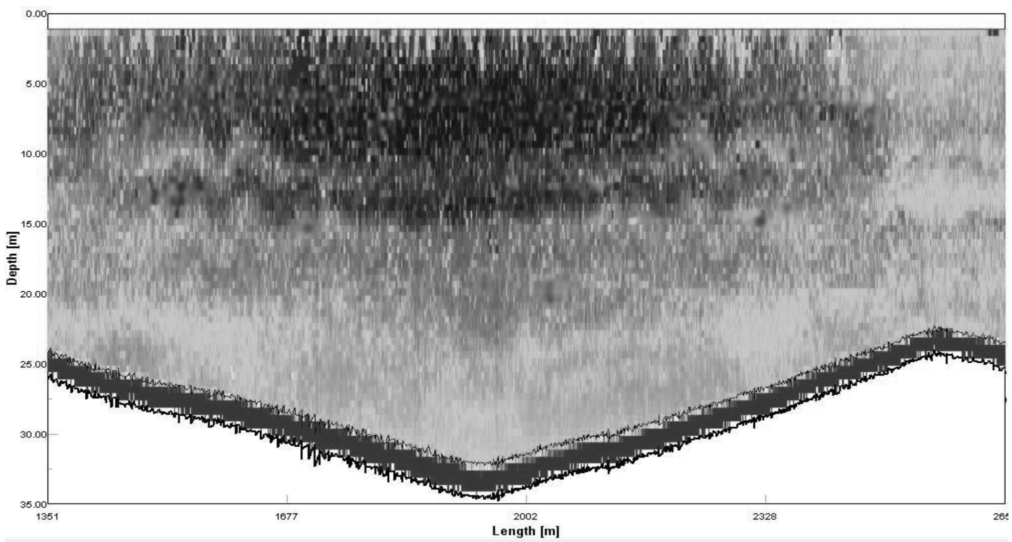


Fig.8 ADCP record of a train of intense internal waves in the coastal sea zone (the backscattered signal)

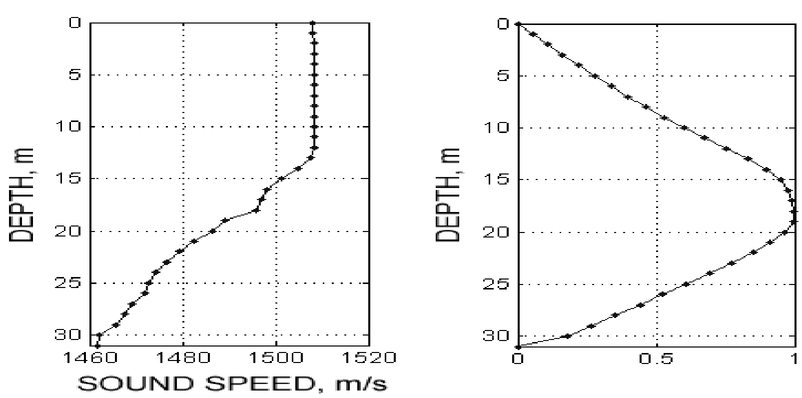


Fig.9 Eigenfunction of the first-mode internal waves and vertical sound speed profile for the corresponding stratification

parameters and one of the sound speed profiles measured in the close vicinity of the reception point, the computer code of Goncharov [4] was used to calculate the internal wave eigenfunctions and the resulting disturbances of the sound speed field on the propagation path (Fig. 9).

We also computed the changes in the signal energy and shape for passing a 6-m internal wave with a plain front that was parallel to the path ($0^o$) and made a small angle ($5^o$) to it. The computation was performed for the signals with a flat spectrum within a band of 1700-2700 Hz. Figure 10 shows the experimental time dependence of the energy in the received signals for the 4-min period of increase in their amplitudes and two calculated curves. The variations of the signal energy and shape for the case when the wave front is parallel to the path well agree with the experimental data in their general features. On the other hand, the time dependence is quite different when there is a small ($5^o$) angle between the wave front and the path. In the latter case, the sound field becomes inhomogeneous along the path and continuously changes when the internal wave crosses the path.

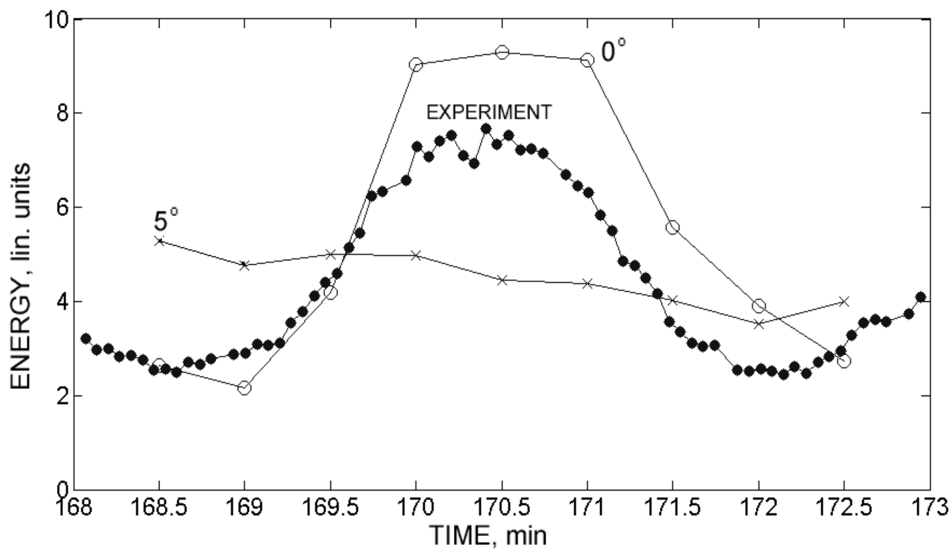


Fig.10 Time variations of the signal energy in crossing the path by the internal wave

## 5. CONCLUSIONS

Long-term acoustic measurements with broadband pulsed signals were performed on a fixed propagation path in a coastal zone of the Black Sea. The experiment was accompanied by continuously measuring the water temperature in the near-bottom layer and surveying the sound speed profile and currents on the path. A high sensitivity of the signal parameters (their shape, propagation time, and energy) to the changes in the hydrophysical characteristics of the medium was revealed. In the experiment, variations of the sound speed field under the influence of the passage of an anticyclonic eddy and internal waves were studied. In particular, the resulting fluctuations of the propagation time for the most intense part of the signal were higher than 2% (17.6 ms) for the 9-day duration of observations on the 1.2-km path. It is worth mentioning that the observed trains of short-period internal waves led to substantial fluctuations in the energy of the sound signals with the frequency of the internal waves. Such a high sensitivity of the signal parameters to the space-time variability of the hydrophysical characteristics of the water column offers a realistic implementation of acoustically monitoring the coastal zones.

ACKNOWLEDGEMENTS

This work was partially supported by Russian Foundation for Basic Research (Projects nos. 05-02-17406, 08-02-00952, and 07-05-00597), and “TRDinstruments-Europe”. The authors are grateful to N. Okhrimenko, V. Poddubnyak, V.Chekida, L. Tarasov, and Eu. Odintsov for arranging the propagation path and participating in the experiment. We also thank A. Zatsepin of Shirshov Institue of Oceanology RAS for providing the data of vertical surveying the water column.

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