LOCAL ACOUSTIC TOMOGRAPHY ON SHELF OF THE BLACK SEA

VALERIY GONCHAROV[1], BORIS KURYANOV[1],
ANDREY SEREBRYANY[2]

[1]Shirshov Institute of Oceanology, RAS
Nakhimovskiy Pr., 36, Moscow, Russia
gvv@ocean.ru, bkur2@yandex.ru
[2]Andreyev Acoustics Institute
Shvernik Str., 4, Moscow, Russia
serebryany@hotmail.com

Using self-contained acoustic buoys developed at the Shirshov Institute of Oceanology, experiments were performed to verify the possibility of acoustic tomography in a local region of a shallow-water sea. In the experiments carried out in October 2010 on shelf of the Black Sea, compound phase-manipulated signals are transmitted and the time responses of the medium are measured using three bottom-moored receiving and transmitting transducers separated by 1-km distance. The results of reconstructing the sound and current velocities are compared with the data of independent measurements made by set of standard oceanographic instruments (ADCP, CTD sounds, etc.).

INTRODUCTION

The objective of our work is to study the possibilities of acoustic tomography in shallow water sea regions where surface and bottom reflections are important. In contrast to a deep sea, sound propagation in such regions is accompanied by considerable signal instability; this feature leads to certain skepticism on the part of some researchers in the possibility of identifying rays and implementing acoustic tomography in shallow water seas. On the other hand, the use of high frequencies for local experiments in a shallow water sea makes it possible to develop simple instruments and does not require high expenditures on performing experiments.

To perform the aforementioned studies, the Institute of Oceanology RAS developed fully self-contained bottom surface buoys equipped with reversible acoustic transducers, transmitting and receiving amplifiers, non memory intensive computers controlling the experiment, and systems for the precision time synchronization of independent buoys with the

use of GPS positioning. Such systems can promptly be deployed in different regions of a shallow-water sea.

1. INSTRUMENTS USED

The acoustic buoy system was used in the maritime experiment performed in October 2010 continuously over the course of a day. Three acoustic buoys were deployed at the shelf of the Black Sea, southwest of Golubaya Bay, at a distance of 2 to 3 km. The path between buoys 1 and 2 passed nearly along a line of equal depths (about 41 m). Station 3 was deployed at a depth of about 46 m, the bottom along all the paths being nearly planar. All three independent computers generated clipped broadband M-sequences with a complexity factor of 2047, a center frequency of 10 kHz, a bandwidth of about 2 kHz, and a duration of approximately 1 s. The signals of the other buoys were also recorded with a sampling frequency of 100 kHz. Different buoys transmit signals in series, every 3 s, the repletion period of the transmissions being 9 s. During the experiment, 9000 arrivals were recorded for each buoy. The accuracy of synchronizing the transmissions of different buoys was about 10 μs. To obtain time responses of the medium on different paths, the processing of the recorded signals involved in band filtering around 10 kHz and calculation of the correlation function of the received signals with duplicates of transmitted ones. Thus, we obtained the functions of the medium's responses for the three paths, for direct and reverse propagation. Those data are required to calculate the sound velocity and current velocity projections on the propagation path along different rays and to reconstruct the value and direction of horizontal currents.

2. OCEANOLOGIC MEASUREMENTS

For performing the tomographic experiment, we needed the data of the medium parameters at the experimental site, those data being obtained by an independent method, that is, by standard hydrophysical measurements.

The measurements of the medium background were performed from a yacht equipped with an acoustic Doppler current profiler (ADCP), Rio Grande 600 kHz. Also, a compact probe mini SVP produced by Valeport Company was used. This device measured the sound speed, temperature, and the depth of the water column. The declared accuracy of measuring is 0.02 m/s for the sound speed and 0.05% for the depth. In addition, in the vicinity of the triangle of buoys, an anchored mooring was used. This mooring equipped with 9 thermistors was placed at a depth of 34 m and worked for a number of days.

Within October 6 to 8, three passages of the yacht were performed. On the first passage of October 6, information on the currents was collected and the position of thermocline was determined before the beginning of the tomograhic experiment. The yacht with current profiler made a tack from Golubaya Bay in the direction close to the normal to the coastline, with a station near the mooring equipped with a thermistor chain (the mini probe was used). Then, the yacht went a countertack and returned back, with the measurements at several points. Measurements of October 7 and 8 differ from those of October 6 in that, after the standard tack through the point of the anchored thermistor chain, the yacht went to the triangle of self-contained acoustic buoys and then passed over its perimeter with stopping for mini-probe-measuring at upper points of the triangle.

Figure 1 presents information on the mean currents for the measurements of October 7 and 8. It is worth mentioning that, in those cases, the passages of the yacht corresponded to north-east winds of an intermediate strength. The measurements of October 6 revealed a uniform north-west current over the entire near-coast part of the shelf, with a velocity of about

0.2 m/s. The current covered nearly the entire water bulk of the whole tack in the coastal sea region. The measurements of October 7, at 16.40, showed that the regime of currents at the shelf strongly differs for the passed day (see Fig. 1). At the most part of the tack (in the coastal region), the current becomes of the south-east directivity that changed counter-clock-wise at a 4-km from the coastline to the opposite one. Thus, we detected an anti-cyclonic eddy with a radius of about 4 km. At the outside of the eddy in the coastal region, the current velocity reached 0.40 m/s. Eddies of similar type in the Black Sea are formed by so-called bimodal currents in the coastal region, with changing their directivity to an opposite one. The next measurement of October 8, at 13.20, does revealed no anti-cyclonic eddy but, instead, a noth-west current was detected (see Fig. 1). However, the current turned to south as the distance from the coast increased, this feature being likely an indication of passing a cyclonic eddy to the experimental site at that time.

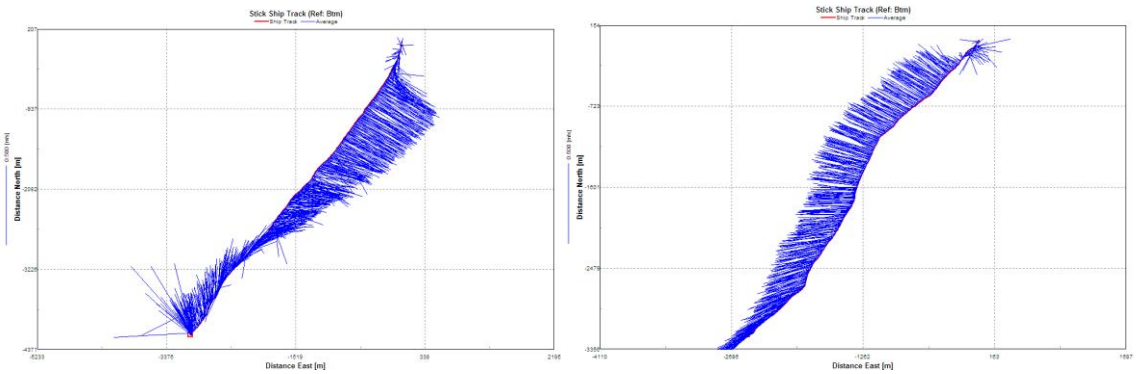

Fig.1. Changes in the mean current on October 7 (at the left) and October 8 (at the right) indicating the existence of an anti-cyclonic eddy at the shelf on October 7.

A characteristic feature of the presence of an anti-cyclonic eddy is an existence of a maximum in the current in the coastal region and the following decrease of the current velocity in deeper regions of the shelf. Such a feature is can be well seen on the data of October 7 (see Fig. 2). At the same time, the measurements of October 8 without the eddy show a uniform distribution of the current velocity, independently of the distance from the coastline.

Another useful information offered by ADCP consists in the data on sound backscattering over the entire water bulk. Figure 3 shows the patterns of backscattering for the measurements of October 7 and 8. In the both cases, one can well see the position of the thermocline (it is near a horizon of 30 m). The data of October 8 show an extensive arrear of enhanced backscattering, with a a horizontal size of about 2 km. Such an effect, among other sources, can be attributed to the pollution of the sewage from the Gelendgik town, which are carried by the north-west current flowing along the coast. The quality of the signal obtained on October 7 is worse because of a high sea state.

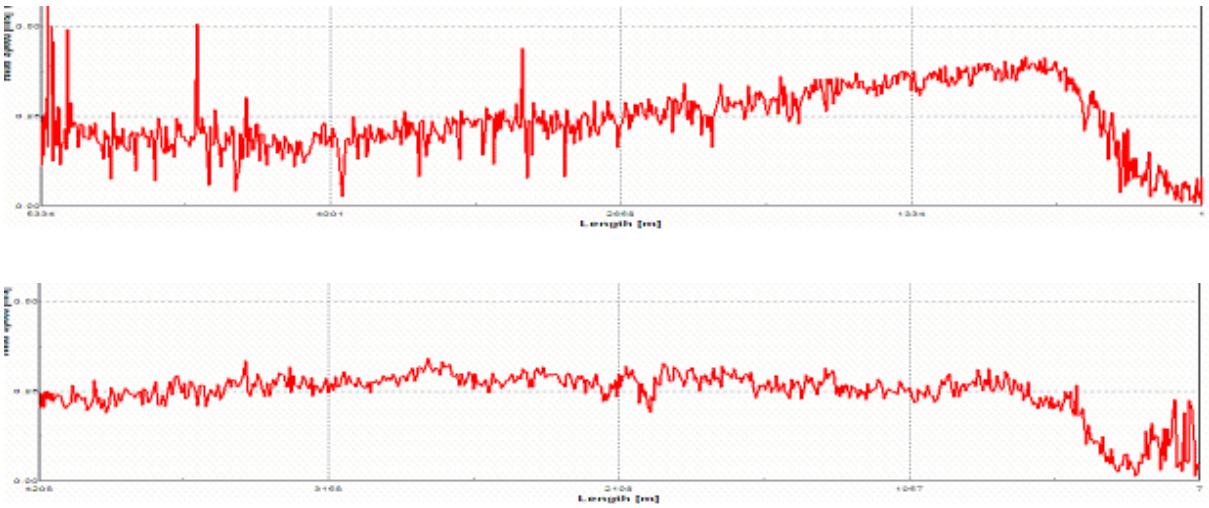

Fig.2. Characteristic change in the current velocity as a function of the distance from the coast on the tacks with the anti-cyclonic eddy on October 7 (at the top) and the absence of the eddy on October 8 (at the bottom).

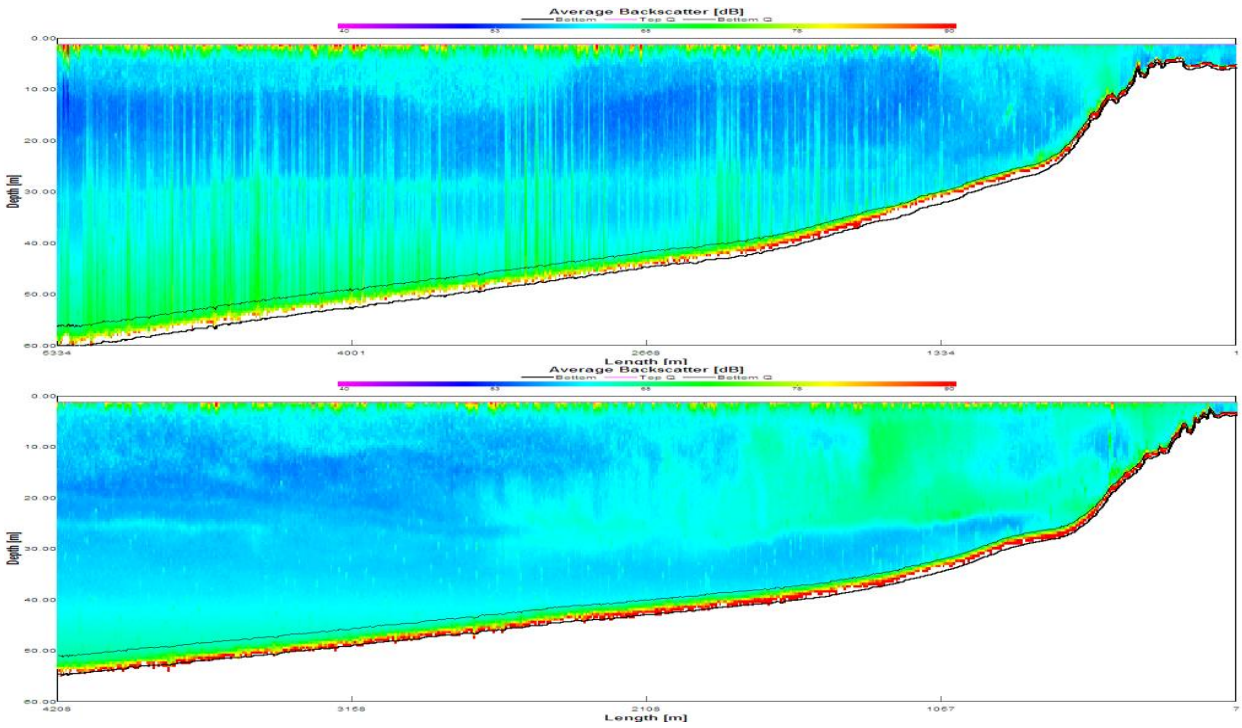

Fig.3. Patterns of volume sound backscattering on October 7 and 8 (from top to bottom).

As we mentioned above, the measurements of October 7 and 8 consisted in passages along the perimeter of the triangle at whose apexes the self-contained buoys were positioned, in addition to the standard measurements from the coastline to the wedge of the shelf. Figure 4 shows the corresponding fragments of the data obtained on October 7 and 8. In the both cases, for a length of 1 km of the triangle, the velocity and the direction of the current was constant for the time of measurements, that is, those quantities were uniform. Of course, this

phenomenon affords the determination of the nedium parameters by using the tomographic scheme. At the apexes of the triangle, the yacht drifted for several minutes and, as a result, it was strongly carried by the current. The measured sound velocity profiles are shown in Fig. 5. The vertical sound-speed profiles exhibit an upper quasi-uniform layer with a thickness of 25 m and a sound speed of 1500 m. Deeper, an abrupt discontinue layer (picknocline) follows, with a sound speed of 1470 m/s and lower. Such a characteristic depth dependence can be attributed a strong time variations of the water parameters, which took place during the tomographic experiment. This figure also presents the three-layer approximations of the sound velocity profiles used in calculating the ray patterns. These data show that a sharp thermocline existed, as usual, in autumn and summer. The upper layer has a nearly constant sound velocity and the near-bottom layer has a slight constant gradient.

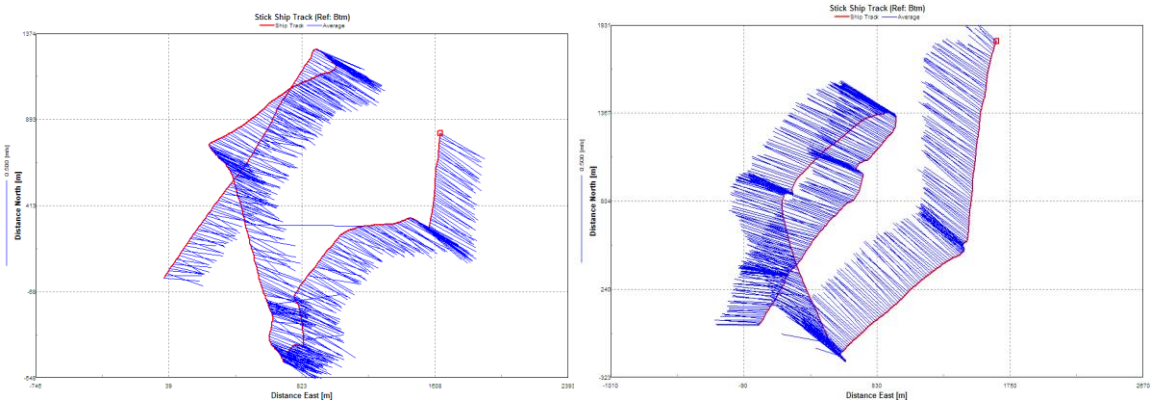

Fig.4. Variations of the mean current velocity over the area of the tomographic site on October 7 (at the left) and 8 (at the right).

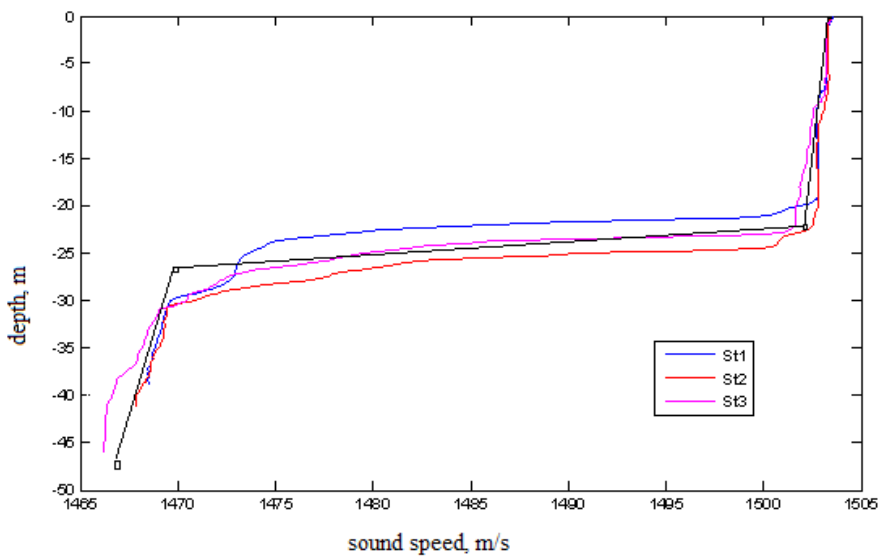

Fig.5. Sound velocity profiles in the vicinity of the three buoys (indicated by numbers of lines) during the experiment (4th–5th hours).

3. RESULTS OF TOMOGRAPHIC EXPERIMENT

Figure 6 a shows a typical pattern of pulse responses of the medium on path 1–2 with transmission by buoy 1 and reception by buoy 2. Similar patterns are obtained for other paths and for propagation in reverse directions (Figure 6б and 6в). An example of signal arrivals for reverse propagation on path 1–2 is shown in Fig. 6a. Those data have been obtained during hydrological measurements (4th–5th hours marked by arrows in Fig. 7). Figure 7c presents ray patterns calculated for path 1–2. Those patterns are required to identify the experimentally obtained ray arrivals corresponding to the period of hydrological measurements. According to the calculation, there are several tens of eigenrays that compose several close groups of arriving rays, whose ordinal numbers are sequenced corresponding to increasing time delays. The fastest group 1 corresponds to the quartet of rays with single reflections by the surface. In the arrival time, this group contains rays without surface reflections, with single turning points at a horizon higher than 20 m (in the nearly uniform layer). Groups 2 and 4 are composed by rays that do not reach the surface and are refracted in the vicinity of the thermocline; these rays have two or three cycles of bottom reflections.

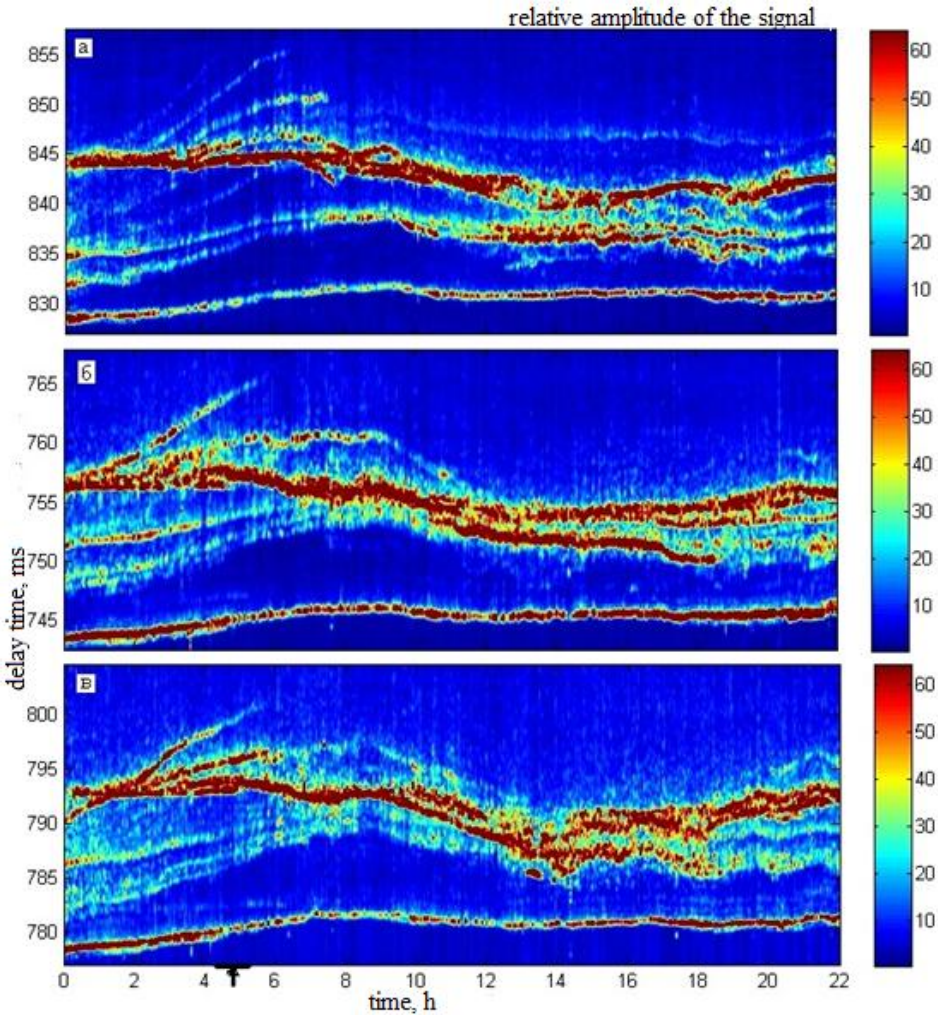

Fig.6. Impulse response of the medium on path 1–2 (a), 1-3 (б) и 2-3 (в) showing the change in travel times for different groups of signals. The entire duration of the record is 22 h, with a repetition rate of 9 s. The abscissa corresponds to current time from the beginning of the experiment, and the ordinate indicates the travel time of the signals in milliseconds.

Between the arrival times of the aforementioned groups, there exists a ray group 3 twice reflected by the surface. Closely following are ray groups 5, 6, and 7 that propagate in the near-bottom layer, below the thermocline, and have several cycles of bottom reflections; the intensity of these rays is maximal. The last arrivals correspond to ray group 8, which have three surface reflections. Those rays are the steepest and have turning points near the lower boundary of the thermocline. Figure 4a serves to compare the calculated and experimental data for path 1–2 (5th hour), which are averaged over the second minute-long interval. Here, the solid line shows the signal amplitude obtained theoretically by incoherently summing the ray signals calculated in view of their amplitudes, arrival times, and bandwidths. The thin and dashed lines correspond to experimentally obtained arrival times for direct and reverse propagation, respectively. These data are subsequently used in calculating the values of the sound velocity and projections of the current velocities on the path. Comparison shows that the experimental arrival times correspond rather closely to the ray-calculated ones, especially for the most intense ray groups 1 and 5–6. As for the other experimentally obtained arrivals, they correspond worse to the calculations (Fig. 6). According to Fig. 6, four to eight groups of signals can be observed. In principle, those groups could be sufficient to determine the parameters of simple models for the sound velocity profiles with several layers. However, all

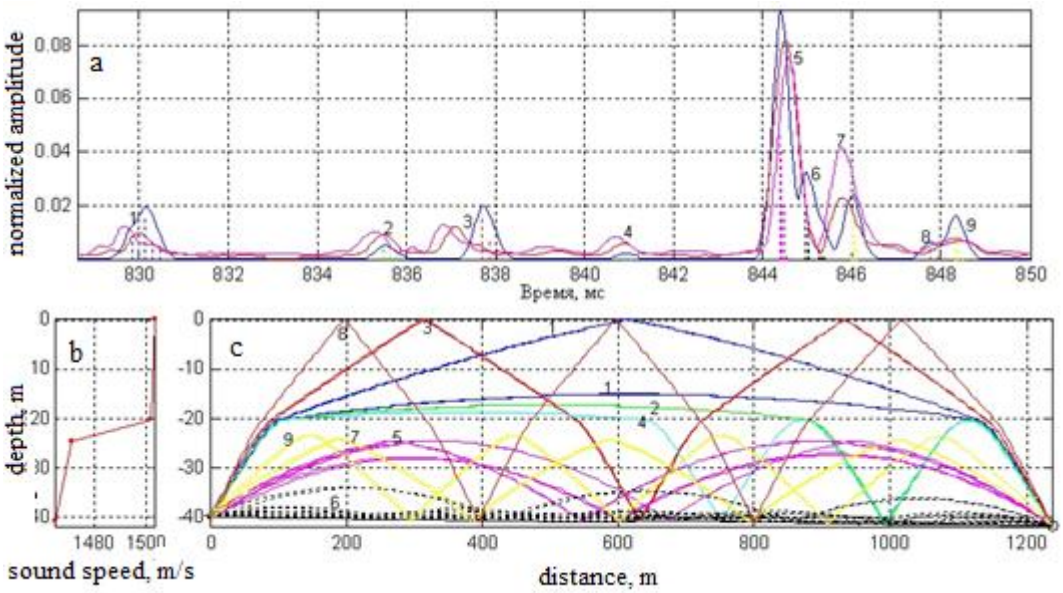

Fig.7. (a) Experimental responses for direct (thin solid line) and reverse (dashed line) propagation of signals and calculated response (thick line). (b) Reference sound velocity profile close to the measured one (Fig. 1). (c) Ray trajectories for different groups.

the signals can hardly be identified: the experimental pattern of the arrivals exhibits irregular variations in time. Sometimes, the observed ray trajectories arise, merge, and vanish as time progresses. Such phenomena lead to the impossibility of using the linear theory of reconstructing the sound velocity profile and the profile of currents using a single reference model [1]. Therefore, the reconstruction was performed by the so-called method of matched time responses [2], which, in particular, allowed us to calculate and adjust the lengths of paths 1–2, 1–3, and 2–3 yielded by the GPS data at the locations of the buoys. This procedure also used the measured sound velocity profiles (Fig. 5). Those lengths were 1236, 1161, and 1107 m, respectively. The adjusted lengths were used in subsequent calculations. Only two types of

the most intense signals can be easily identified—those reflected by the surface and refracted in the near-bottom layer. Because of the complexity of identifying the remaining signals, we first reconstructed the averaged values of the sound velocity and current velocities using the aforementioned two types of the most stable signals. In this case, the simplest two-layer model of the sound velocity and current profiles was used according to the Munk method.

Figure 8 shows the result of reconstructing the mean sound velocities in the near-surface and near-bottom layers, along with shifts of the interface between these layers. It is noteworthy that the corresponding dependences are relatively close for all three paths, and their variations are similar for the entire experiment. Such a phenomenon indirectly indicates weak horizontal variability of the sound velocity field. However, slight but noticeable variations in the aforementioned parameters exhibit themselves for different paths. That variability manifests itself more strongly in the reconstructed mean currents in the reference layers. The projections of the currents on all three paths were calculated and then recalculated to horizontal vectors of the currents, either for arbitrary pairs of paths or simultaneously for all three paths.

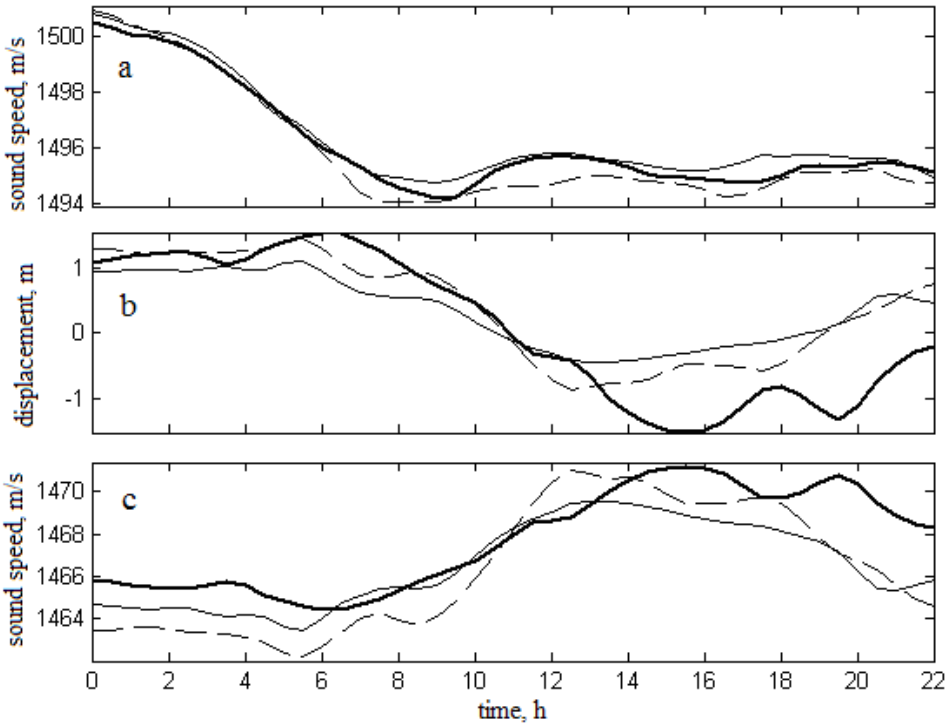

Fig.8. Changes in the sound velocity reconstructed from the arrival times of signals for (a) near-surface and (c) near bottom layers and (b) the shift of interface between these layers. The data for paths 1–2, 1–3, and 2–3 are shown by thick, thin, and dashed lines, respectively.

The results of current reconstruction are shown in Fig. 9 in polar coordinates. Here, the changes in the mean current vectors are presented for the near-surface layers over 22 h of the experiment (each point is the result of averaging over half an hour). Figure 5 also contains the data obtained by the standard ADCP instrument at only two points, in the 5th and 25th hours of the experiment (we could not use the ADCP at intermediate points because of the stormy weather). According to these data, the direction of the current became nearly opposite during the day, from southeast to northwest, both methods indicating this. Simultaneous

measurements of the mean current velocity by the two methods used in the 5th hour from the beginning of the experiment yield close results.

Similar patterns of changes in the mean currents obtained by reconstruction for other pairs of paths and, on average, for all the three paths led to close results for the near-surface layer (as in Fig. 8) but proved to differ more for the near-bottom layer. Relatively rapid (less than half an hour) variability, in both the value and the direction of the current in the near-bottom layer was revealed (not shown on the Figure). Because the current velocity in that layer is not high, we can suppose that a noticeable contribution to its formation comes from dynamic processes in the vicinity of the thermocline, relatively short trains or solitons of internal waves, for instance. The calculation of the buoyancy frequency obtained using the measured hydrological data and the parameters of internal waves showed that the currents caused by those processes reach 10 cm/s, with an amplitude (a vertical shift in the thermocline) of about 1 m for waves with periods from 10 min to 1 h. To verify this hypothesis, it is necessary to reconstruct both the sound velocity and current profiles in more detail, for instance, by using the method of matched time responses, which, in particular, can reveal relatively short oscillations of the thermocline.

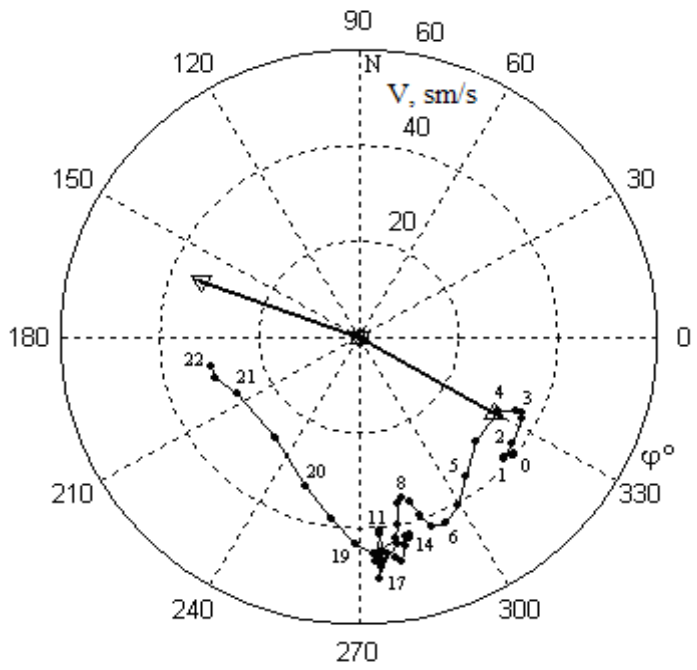

Fig.9. Comparison of changes in the vectors of mean current velocities for (a) near-surface obtained with high-frequency acoustic tomography for 22 h of the experiment (points of experiment are separated by half-hours) and two measurements with the ADCP in the 5th (330°) and 25th (160°) hours (arrows).

4. CONCLUSION

The data of these studies result in the conclusion that high-frequency acoustic tomography is a good addition to the widely used method of measuring currents with ADCP instruments, in view of the fact that the latter can yield incorrect results in the absence of volumetric scatterers or in the presence of quickly moving fishes.

ACKNOWLEDGEMENTS

This work was supported by Russian Foundation for Basic Research, projects no. 10-05-00804a, 08-02-00952a, 10-02-10021k and by the Basic Research Program of the Russian Academy of Science Presidium “World Ocean” project no. 18.

REFERENCES

[1] W.H. Munk, P. Vorchester, and C. Wunsh, Ocean Acoustic Tomography, Cambridge: Cambridge Univ. Press, 1995.

[2] V.V. Goncharov, Method of matched time responds in ocean acoustic tomography, Acoustical Physics, 1997, V. 43, № 5, pp. 622-629.