ISSN 0027-1349, Moscow University Physics Bulletin, 2009, Vol. 64, No. 2, pp. 202–207. © Allerton Press, Inc., 2009.
Original Russian Text © V.S. Ivanov, P.N. Kravchun, 2009, published in Vestnik Moskovskogo Universiteta. Fizika, 2009, No. 2, pp. 92–97.

The Influence of the Benthic Frontal Zone on Acoustic Wave Propagation in the Ocean and Evaluation of the Possibilities of its Ray Tomography

V. S. Ivanov and P. N. Kravchun

Department of Acoustics, Faculty of Physics, Moscow State University, Moscow, 119991 Russia
e-mail: kravchun@phys.msu.ru

Received March 24, 2008

Abstract—The specificity of ray trajectories in the presence of a benthic front, which is the boundary between the Antarctic deep and bottom waters, has been considered. Deep-water “noncanonical” caustic surfaces confined to the front have been found. The ability to reconstruct a sound velocity profile in the benthic frontal zone has been evaluated using methods of ray tomography in the ocean. A possible reconstruction of the profile using a horizontal displacement of the receiving antenna or transmitter at relatively small depths has been shown.

Key words: benthic frontal zone, acoustic wave propagation in the ocean, ray acoustic tomography, basin, noncanonical caustics, sound velocity profile, reconstruction.

DOI: 10.3103/S0027134909020210

The study of the frontal zones of the World Ocean is one of the most relevant trends of physical oceanography. Of special interest are the quasi-stationary large-scale fronts delimiting the boundaries of waters and dynamic structures of the World Ocean. Fronts substantially effect the propagation of acoustic waves in the ocean strata.

The largest among the types of ocean fronts is the benthic front. It is formed at a large depth as the result of Antarctic bottom water propagation in the bottom layer from Antarctica to the north. The Antarctic bottom water forms mostly in the Weddell sea, resulting from cooling and salination (mineralization) during the cold part of the year. Descending along the continental slope due to high density, the Antarctic bottom water moves with the Antarctic circumpolar current and enters the basins of the Pacific, Atlantic and Indian oceans through deep-water passes, permeating all deep-water bottom structures. A benthic front, which falls into the class of quasi-stationary thermohaline fronts, appears as an almost horizontal surface of the boundary between Antarctic bottom water and the deep water of the respective ocean.

A benthic front differs from other types of oceanic fronts in the following characteristics: (1) large depth of bedding (from 2000 to 5000 m depending on the region); (2) the almost horizontal position of the frontal zone; (3) the huge areas of the frontal surface, proving the global character of the phenomenon; (4) high values of temperature gradients in the layer of the benthic thermocline—up to 1.5°C/km, which is comparable with the temperature gradients of the “Northern Wall” in the Gulf Stream; (5) the relatively small thickness of thermo-, halo- and pycnoclines, according to the front (200–500 m); (6) the low mutability of the benthic frontal zone.

Benthic fronts have been studied relatively little, since they are difficult to access for experiments. Only a few works so far have dealt with benthic fronts and all of them relate to the Pacific Ocean (see, for example, [1–3]). Studies of benthic front impacts on acoustic fields are only beginning. At present, only preliminary evaluations of the effects of benthic fronts in the ray approximation and only in the Pacific Ocean [4] have been carried out and the influence of benthic fronts on the mode structure of acoustic waves has been studied [5].

At the same time, a wider investigation of benthic fronts and associated acoustic phenomena is of great interest, which could be based on new data obtained during the large-scale International Oceanological Experiment WOCE (World Ocean Circulation Experiment). This experiment featured global coverage of the World Ocean area at all depths from the surface to the bottom, as well as the precision of the obtained data (CTD-profiles were recorded with a resolution up to 2 decibars).

Analysis of the hydrology data of the WOCE experiment allows us to conclude that the most expressed benthic fronts are formed in the regions of intensified Antarctic bottom water motion: deep-water passes, transform break-ups and deep-water basins with intense circulation of Antarctic bottom water. The upper boundary of the benthic frontal zone in these

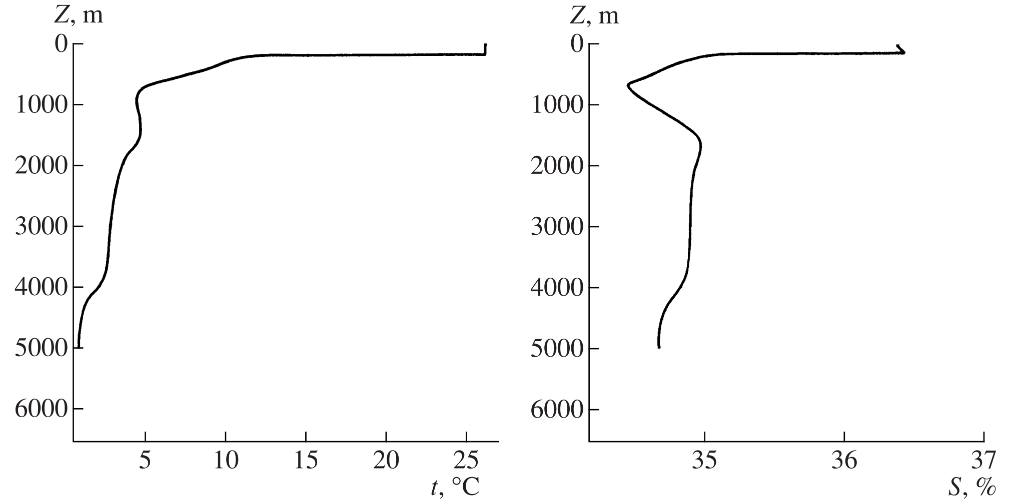

Fig. 1. Profiles of in situ temperature and salinity in the region with the expressed benthic front (Atlantic Ocean, North-West of the Brazilian basin). Data of WOCE experiment: open-cast 05MT22/2, point 719, 30.5 W/5.067 S.

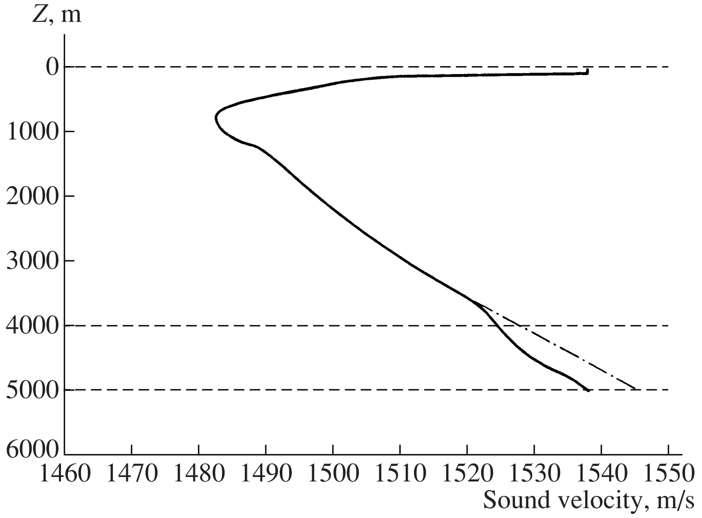

Fig. 2. Profile of the sound velocity in Northeastern region of the Brazilian basin (data of WOCE experiment: open-cast 35A3CITHER1/1, 20.835 W / 4.497 S). Dotted line, extrapolation of the profile with grad values c(z) in deep water (reference profile). Depth of the location, 5000 m; depth of the frontal surface bedding, 4000 m.

areas can be observed at depths from 3000 to 4500 m. As a rule, in the frontal zone both thermal and salinity fronts (Fig. 1) become clearly apparent. In the layer of the benthic pyknocline there is a small but clear local maximum of the Vaisala–Brent frequency that can aid the more intense development of internal waves. At the depths of the frontal zone in all cases a decrease of the vertical gradient of the sound velocity can be observed (Fig. 2).

The objective of this work is to study impact of benthic fronts on the acoustical field in the ocean in the ray approximation and investigation of the possible reconstruction of the profile of the sound velocity in a benthic frontal zone by the methods of ray tomography of the ocean.

To calculate ray trajectories, software has been developed in C++. The software uses data on the real hydrology obtained by WOCE experiments. In this work, the results of numerical calculations are presented for the hydrology of the Northeastern region of the Brazilian basin (Fig. 2).

In the presence of a benthic front the layer with the lower values of the sound velocity gradient is formed at large depths. A ray passed through such layer would undergo either a slowing down or speeding up (compared with the case of no benthic front) depending on the angle of the ray outgoing from the source, i.e., practically depending on the maximum depth of ray penetration. From Fig. 3 it can be inferred that the ray picture in the ocean changes greatly under benthic front influence compared with the well-known case of the

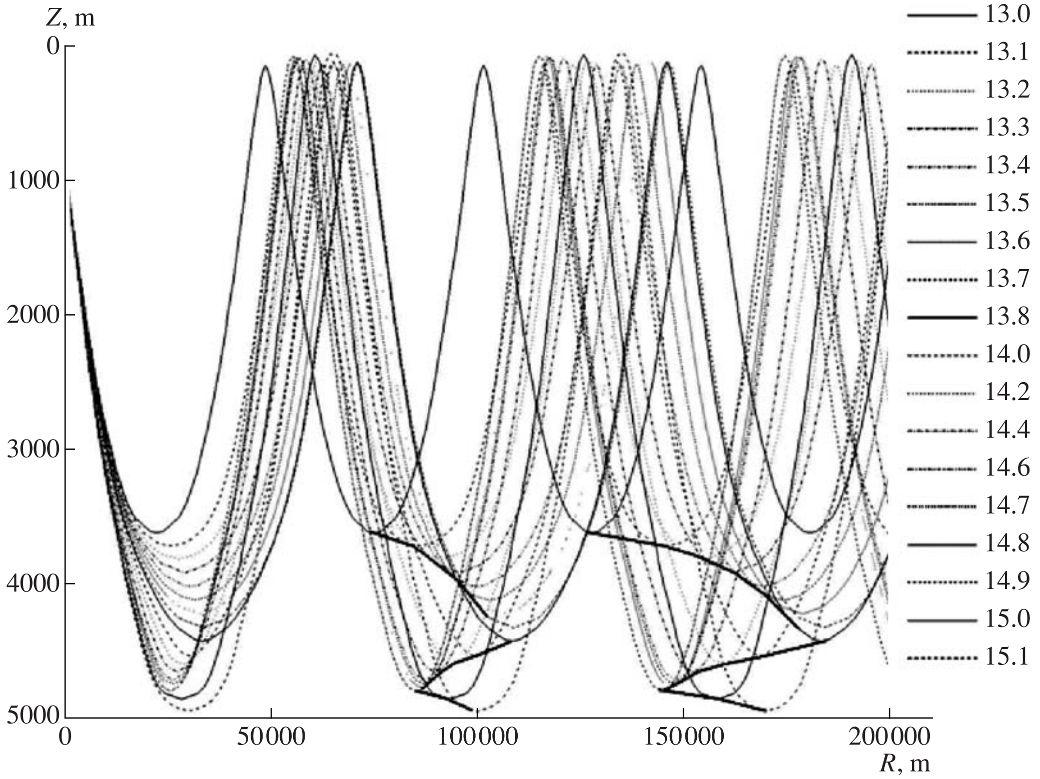

Fig. 3. Ray trajectories in the regions with an expressed benthic front (Atlantic Ocean and Brazilian basin). Deep-water caustics are marked with bold full lines, on the right, the angles of the outgoing rays are given.

"canonical" profile of the sound velocity. Due to the decrease of the sound velocity gradient at a depth of 3600–4500 m, rays go through the lower layers with a larger trajectory radius and accordingly the length of the ray cycle as a whole increases. For the selected hydrology, the cycle length can increase 1.4 times due to the benthic front effect. With an increase of the outgoing ray angle, the ray will penetrate deeper than for 4500 m, i.e., into the layers where the sound velocity gradient increases (the layer with a small sound velocity gradient is passed by such rays at a rather large angle and the time of sound propagation in this layer is relatively small). Therefore rays outgoing at a large angle and penetrating lower than the benthic thermocline can rise to the surface earlier than those outgoing at a lesser angle. This does not happen in the case of the canonic profile of the sound velocity.

In Fig. 3 it is apparent that the caustic system also undergoes modification due to the specific hydrology bound with the benthic frontal zone. New noncanonical caustics arise in the layer of the Antarctic bottom water, having an incidence and localization that do not coincide with the caustics of noncanonical ocean hydrology. In this case, caustic surfaces lying higher than the bottom ones lose their sense of boundaries between the lightened zone and the shaded zone. New noncanonical caustics belonging to the Antarctic bottom water layer can be called benthic, like the front to which they are attributed.

The calculations for a track with a fixed length (we denote the track as the distance across and between the points of radiation and reception) show that the time of propagation among the rays that go through the benthic frontal zone noticeably increases compared with the case when the benthic front is absent: the time of track passage with the length of 100 m may increase by 0.5 sec, in this case, the depth of the ray passage could significantly change.

As a whole, the propagation of sound waves in the presence of an expressed benthic front is characterized by the following:

(1) the length of the ray cycle running through the frontal zone increases by 20–40% (in the considered case, up to 25 km);

(2) the zones of secondary light on the surface move away from the source (the first zone by 5–25 km, the second one by 10–50 km, etc., which reaches 40% of the distance between the source and the respective zone);

(3) a spatial shift of the caustic systems is observed (the caustics closest to the source move away by 8–12 km);

(4) systems of noncanonical benthic caustics lying in the Antarctic bottom water layer emerge;

(5) the depth of the ray permeation with equal outgoing angles increases by 200–500 m.

This fact helps us to reconstruct the sound velocity profile in the benthic frontal zone using the methods of acoustic tomography of the ocean. This goal is of special interest because the front is hard to reach in order to perform in situ investigations.

We first examine the traditional scheme of acoustic tomography of the ocean in which a static transmitter and vertical receiving antenna are used. Using such methods, information on the depth of the arrival of the rays and time of signal propagation over the track can be obtained. Consider as a reference ("a priori") the sound velocity profile complying with the case where a benthic front is absent (the sound velocity gradient at great depths in this case is extrapolated by its values in the deep water, as is shown by the dotted line in Fig. 2), i.e., the reference is the canonical profile. We shall also call the respective ray trajectories "references." A sound velocity profile reconstruction in the benthic frontal zone can be made by introducing corrections into the reference profile; these minimize the time delays endured by the calculated rays compared with the real rays when a benthic front is present. In this work the "real" rays are the ones calculated on the basis of the hydrology data of WOCE experiments (i.e., real hydrology of the respective ocean region).

To evaluate the possibility of sound velocity profile reconstruction in the benthic frontal zone we have calculated the differences in the arrival times of the real and reference rays for a stationary track with a length of 100 km. The delay of the real rays, as the calculations show, is rather significant: for some outgoing angles they attain 0.5 sec. In this case, the depth of the real and reference ray penetration can differ by 400–500 m, which is also fairly large.

An important factor for the solution of the problems of ocean tomography is the spatial location of the receiving system. The optimal distance between the transmitter and the receiving antenna lies, in our opinion, within the limits of 100–150 km, since for a shorter track, ray resolution becomes more difficult and for a longer one the factors destabilizing the sound field (variability of the hydrology parameters of the medium, noises, etc.) become more significant. In this case, the antenna should be at the depth that provides the reception of rays carrying maximum information on the studied object. In our case, these are the rays having their introversion depth in the benthic frontal zone.

A convenient characteristic of the acoustic field in the ocean that serves to determine the optimal depth of the receiving antenna location is the $Z(\alpha)$-diagram, which is the dependence of the incoming ray Z horizon on its outgoing (from the source) angle α (for a fixed length of track). Figure 4 demonstrates an example of a $Z(\alpha)$-diagram for the Brazilian basin for real and reference rays (with a transmitter depth of 1000 m). The range of outgoing ray angles in Fig. 4 agrees with the introversion depths lying in the benthic frontal zone.

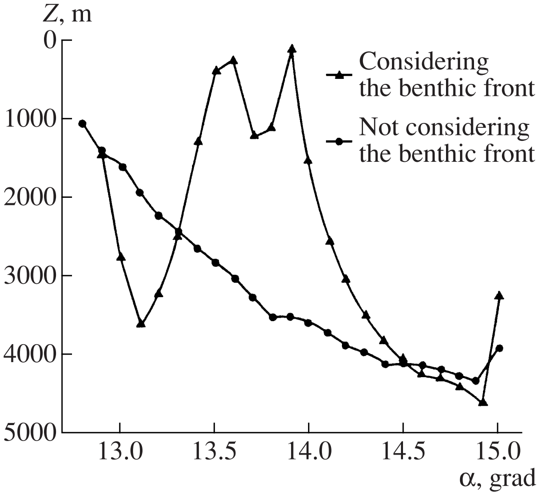

Fig. 4. Z(α)-diagram for a track of 140 km length.

To solve the tomography problem, the depth of the incoming reference and real rays should differ only slightly and the rays coming to the antenna should be far from the caustics, the extreme points of the dependence $Z(\alpha)$. Otherwise, even small variations of the sound velocity profile can result in the disappearance of the existing rays or the emergence of new ones that prevent their use as reference ones [6]. However, from Fig. 4 it can be inferred that $Z(\alpha)$-diagrams for real and reference sound velocity profiles significantly differ: for the real profile $Z(\alpha)$ the diagram has several extremums, complying both with the normal and benthic caustics, whereas the diagram for the reference profile has no more than one extremum, complying with the normal caustic. The number of rays coming to the receiver at the given depth is also different, which complicates ray selection. Finally, the ranges of outgoing angles with similar depths to the incoming reference and real rays are extremely small, which substantially complicates selection of the depth for the receiver location.

In general, from Fig. 4 it can be inferred that changing the velocity gradient in the benthic frontal zone has a strong impact on the character of $Z(\alpha)$-diagrams, which complicates the selection of the place for the receiving antenna location. Zones of depths with similar locations of both reference and real rays cover a small number of rays and often lie deeper than 2500 m. However, it is desirable to select the region where the rays reach the antenna at least up to 1000 m (otherwise there is no point to solving the problem by acoustic methods). This problem gets more complicated, since the real ray runs at depths less than 1000 m (in the vicinity of the surface zone of the secondary light), only 13–18% of its track length and the ray cycle length increases in average for 20–40%, which results in a significant shift of the zones with secondary light. In other

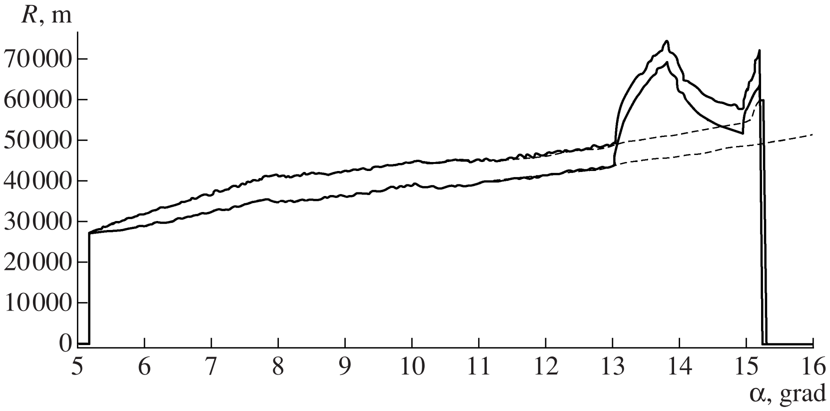

Fig. 5. R(α)-diagrams for real (full curves) and reference (stroke curves) hydrology, depth of ray reception, 500 m.

words, with the use of individual receivers or short vertical antennas, finding the optimal receiving point on the basis of the reference canonic profile is practically impossible. Moreover, in order to improve the accuracy of the tomography problem solution, it is necessary to increase the number of the received rays, which is rather difficult in this case.

Thus, for the standard scheme of ocean tomography (the reception of rays by a vertical antenna at a fixed depth) there is a need for highly accurate a priori information on benthic front hydrology (the canonic profile of sound velocity cannot be the reference one) or it is necessary to use an extensive vertical antenna with a length of not less than 2 km, which inevitably causes technical difficulties and a cost increase of the overall acoustic system.

Therefore, we have considered another scheme of sound velocity profile reconstruction in the benthic frontal zone: tomography with the use of a stationary transmitter and a movable cross receiver or receiving antenna (or stationary receiving antenna or movable cross transmitter).

To evaluate the potential of this scheme we built $R(\alpha)$-diagrams representing the dependence of the distance of the ray coming to a certain depth on its outgoing angle. These diagrams are convenient for the analysis of rays during their reception by a horizontally movable hydrophone. $R(\alpha)$-diagrams for the rays that arrive at the horizon of 500 m in the area of the light zone nearest to the transmitter secondary are given in Fig. 5 for the reference (canonic) and real profiles of sound velocity (with a depth of transmitter immersion of 1000 m). For each sound velocity profile the figures present two curves, since two rays with different outgoing angles come into the reception point over the axis of the underwater sound channel. This fact, in particular, proves the necessity of sorting rays by the direction of their arrival in the vertical plane ("from above," "from below") which can be done, for example, with the use of a pressure gradient receiver.

The $R(\alpha)$-diagrams for the real profile of sound velocity (with benthic front) substantially differ from the diagrams for the reference profile, which is conditioned by the details of the ray's propagation in the benthic frontal zone. $R(\alpha)$-diagrams undergo quite an abrupt jump in the range of angles α, agreeing with the rays passed through a benthic front, which agrees with the above conclusions on the impact of a benthic front on the rays' trajectories (the zone of secondary light on the surface moves away from the source for the distance of 22 km at the rays outgoing angles 13–14° and at the further increase of the outgoing angles again approaches to the transmitter). At a decreasing depth of reception, the character of the R(a)-diagrams changes insignificantly. The main difference is as follows: rays with a smaller range of outgoing angles come to shallower depths.

From the calculations it can be inferred that compared with $Z(\alpha)$-diagrams, $R(\alpha)$-diagrams are much more stable in relation to inaccurate setting of the reference profile of the sound velocity: along with the increase of the profile approximation accuracy in the benthic frontal zone, $R(\alpha)$-diagrams gradually approach the diagrams for the real profile with a stable general character of $R(\alpha)$ dependence. The differences of the distances of the reference and real rays coming into the selected surface horizon exceeds 20 km and the time differences of the incoming rays attain 15 sec, which is comparable with the time of ray propagation over the track (about 50 seconds). Such values can be easily recorded in the experiment.

The stated specificity of $R(\alpha)$-diagrams prove the promise of benthic front tomography with the use of radiating and receiving systems movable horizontally at relatively small depths (in particular, dynamic tomography). Among the difficulties of the experimental realization of the considered scheme is the necessity to use a narrow ray transmitter (for example, a parameter oriented transmitter).

Now consider the numerical solution of the ray tomography of the benthic frontal zone. The sought

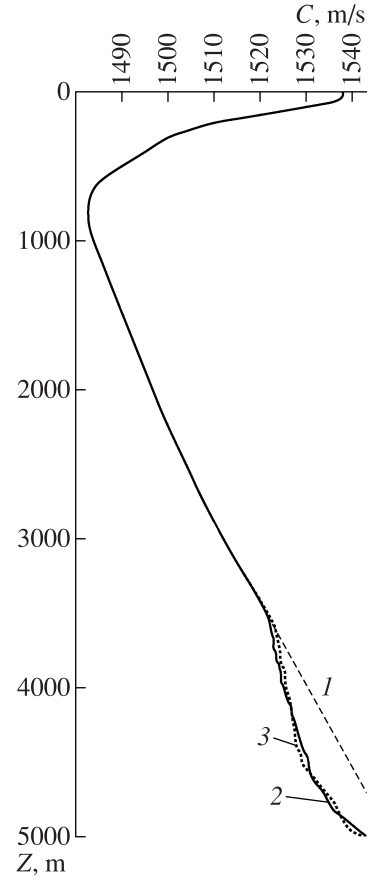

Fig. 6. Sound velocity profiles: reference (curve *1*), real (curve *2*), and reconstructed (curve *3*).

hydrological characteristics will be the sound velocity profile $c(z)$ in the frontal zone and lower, as well as the depth of the upper boundary of the frontal zone. Let the profile $c(z)$ be presented as the value of the reference canonic profile $c_0(z)$ and the polynominal correction of the 4th order $S(z)$ considering benthic front:

$$c(z) = c_0(z) + S(z),$$

where

$$S(z) = \sum_{n=1}^{4} a_n (z - z_0)^n, \tag{1}$$

where a_n is a polynomial coefficient and z_0 is the depth of the upper boundary of the benthic frontal zone. Such a correction serves to rather accurately approximate the real profile of the sound velocity. Thus, the problem becomes the determination of the coefficients a_n and the depth z_0.

To solve the problem we have carried out minimization of the following function:

$$\Omega = \sqrt{\sum_{n=1}^{N} [t(\alpha_n) - t_0(\alpha_n)]^2 + \frac{[R(\alpha_n) - R_0(\alpha_n)]^2}{\beta}}, \tag{2}$$

where n is the ray number, N, is the total number of considered rays, $t(\alpha)$ and $R(\alpha)$ are the time and distance passed by the rays before their rise to the depth of reception, calculated for the profile $c(z)$, $t_0(\alpha)$ and $R_0(\alpha)$ are the time and distance of the similar rays arrival calculated for the real profile, and β is a dimensional factor. The value β was taken as equal to $\langle c_0 \rangle^2$ the average value of the sound velocity at this depth, i.e., so that the weight of the changing ray trajectory and the weight of the changing time of its arrival are equal. It is apparent that the combination of the polynomial parameters $S(z)$, at which the function Ω attains the global maximum, is the problem solution, since it complies with the minimum differences of ray trajectories obtained for the real profile of the sound velocity and for the reconstructed profile $c(z)$.

For the numerical modeling of the benthic front tomography we have selected the depth of the receiver immersion as 500 m, and the transmitter as 1000 m, the time and distance of the coming rays were analyzed for zone of secondary light the nearest to the source. As a result we have obtained the parameters of polynomial correction $S(z)$ complying with the global minimum of the function (2): $z_0 = 3520$ m, $a_1 = 0.009$, $a_2 = 0.013$, $a_3 = -0.029$, $a_4 = 0.0165$.

The results of the problem solution are presented in Fig. 6 with the displayed sound velocity profiles: the reference canonical, the real (WOCE data) and the one reconstructed by the method described above. Note that the solution was obtained at the reference profile, which does not consider the present benthic front at all. In general these results serve to conclude that sound velocity profile reconstruction in the benthic frontal zone is possible by the method of ocean ray tomography with the use of a horizontally movable transmitter or receiving system.

ACKNOWLEDGMENTS

This work was funded by the grant NSH-2906.2008.2

The authors thank Reyener Schlitz (Germany) for the data from the WOCE International Experiment and V.A. Burov (MSU) for useful discussions.

REFERENCES

1. H. Craig, Y. Chung, M. Fradeiro, Earth Planet. Sci. Lett. (16), 50, (1972).
2. Y. Chung, Geophys. Res. **80** (30), 4169 (1975).
3. A. V. Sokov, *Studies of Oceanographic Processes in the Tropical Zone of the Pacific Ocean,* (Moscow, 1989), p. 162.
4. P. N. Kravchun, Acoustic. Journ. **45** (5), 670 (1999).
5. P. N. Kravchun, Acoustic. Journ. **54** (3), 426 (2008).
6. V. V. Goncharov, V. Yu. Zaitsev, V. M. Kurtepov, et. al., Acoustic Tomography in the Ocean, (Nizhniy Novgorod, 1997).