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Identification of rays in a signal registered from the drifting ship

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Possibilities of ray identification in the ship tomography experiment in Western Mediterranean are discussed. The pulse signals (M-sequences) emitted by the stationary source located at the axis of the subsurface acoustic waveguide (the axis depth was 125 m) were registered from the board of the drifting shift. Frequency Doppler shift was compensated. It is shown that in the signal registered by a single hydrophone, depending on the hydrophone depth, arrivals of fours rays with steep grazing angles (at small depths), arrivals of pair or arrivals of individual rays (at greater depths) can be resolved. Due to the drift the distance between the source and receiver was always known with some error. In spite of this fact the measured differences in ray travel times and in travel times of fours of rays were in good agreement with the theoretical predictions obtained using a ray code.

The classical scheme of the acoustic ocean tomography assumes the resolution of rays and their identification by their travel times. Feasibility of ray resolution and identification has been demonstrated many time in the experiments at the stationary acoustic paths. On the other hand, as applied to the situation when a source and/or a receiver are drifting this problem has been studied much less. In this work we discuss the results of the processing of the data obtained in 1994 in the Western Mediterranean where the signals from six transceivers deployed in the framework of the international THETIS-2 project were registered from the board of the Research Vessel "Academik Sergei Vavilov". The objective of the processing under consideration here has been to study individual rays resolution as well as resolution of fours of rays received by a single hydrophone.

During this experiment acoustic pulses with the phases modulated by M-sequences were emitted. We consider here the results of processing of the signals at a carrier frequency of 400 Hz from one of the six sources. The duration of one unit of the corresponding M-sequence was equal to the four periods of the carrier frequency, i.e., 0.01 s. Several times per day the source emitted a series of 10-40 identical pulses. The signals were received at the vertical array tugged by the drifting ship. The array spanned the depths from the surface to 127.5 m with the hydrophones spaced 8.5 m apart. There was also a single receiving hydrophone placed at the depth of 300 m.

According to the data obtained from the CTD casts carried out simultaneously with the acoustic measurements, the underwater sound channel was subsurface with the typical sound speed profile shown in Fig.1. The source was located a little bit deeper than the sound channel axis, at the depth of z=150 m. We have processed the data obtained in the several points located along the same straight line at the ranges varying from 80 to 300 km. The sound speed profiles at all these points were very close to the curve shown in Fig.1.

The results of ray arrival calculations show that the groups of steep rays arrive before the groups of near-axial rays. The difference in arrival times of two successive pulses following steep paths exceeds the difference corresponding to two pulses following paths with smaller grazing angles. At the end of the signal received by the hydrophone located near the waveguide axis there is a large peak formed by a great number of unresolved near-axial rays. The initial part of the received signal usually contains peaks formed by contributions from individual rays or from fours of rays. The rays forming a fours have close horizons of turning points (the number of lower turning points is the same for every ray), but they differ in signs of their launch and arrival angles. The four rays correspond to the four possible pairs of such signs.

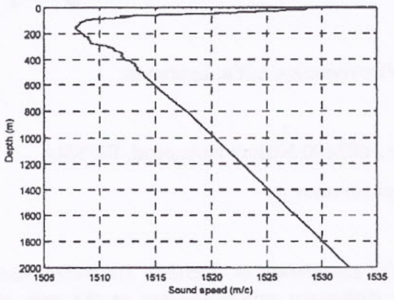

Fig. 1. Typical sound speed profile

During the processing the received pulses were compressed by their correlation with the replica of the initially emitted pulse. The algorithms applied were similar to those which are often used in processing the data obtained in the experiments on the stationary acoustic paths. In addition to such algorithms we have used the method of Doppler frequency shift (caused by the drift) compensation.

The drift of the research vessel changed the temporal scales of the received signal. In general, elimination of these changes requires the forming of the replica taking into account the projection of the drift velocity on the direction of arrival of the ray which we are going to resolve. Nevertheless, since the ray arrival angles are belonged to the rather narrow interval of angles (from -12 to 12 degrees) and taking into account the ray trajectory inclination increases the amplitude of compressed pulse only for a few per cent, we have used the same replica for all ray inclinations.

The drift velocity projection on the direction to the source has been estimated in different ways. For example, we employed the fact that simultaneously with signal registration the ship position had been fixed by GPS measurements. Besides we estimated the changes in pulse repetition period using the received signal autocorrelation function. But most often we simply selected such frequency shift for the replica when the compressed signal registered by the near-axial hydrophone had the largest peak at the final part. Thus, we found the estimation of the drift velocity which later was used to compensate Doppler phase shift at receiving hydrophones.

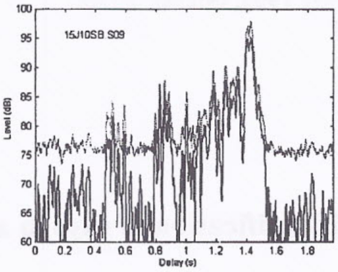

Fig. 2. Results of averaging over 40 pulses.

In Fig.2 the results of averaging over 40 successive pulses are shown. The lower dark curve has been obtained by coherent summation of pulses. The other (lighter) curve represents the result of incoherent summation of pulse amplitudes. The fact that coherent summation leads to a considerably better signal-to noise ration confirms the efficiency of our procedure for the Doppler frequency shift (resulting from the nonstationarity of the receiving hydrophone) compensation.

The complex demodulate amplitudes of the compressed pulses after the coherent averaging are shown in Fig. 3-5. These signals have been registered by one of the receiving hydrophones at different distances. The vertical lines in the figures show the ray travel times calculated using the ray code. The solid vertical lines correspond to the rays leaving the source upward, the dashed lines correspond to the rays escaping downward. Our knowledge of the distance between the source and the receiver was not accurate enough in order to compare the absolute values of the predicted ray travel times to the arrivals of the maxima of the compressed pulse. Therefore we have compared theory and experiment in Fig. 3-5 by shifting all computed ray travel times for the same value to obtain the best concurrence of theory and experiment. Practically it means that we are comparing rather differences in ray travel times than these times themselves.

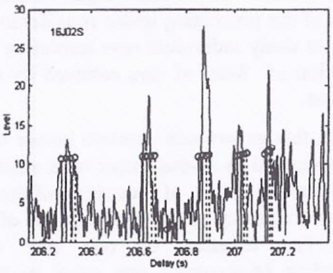

Fig. 3. Envelope of the compressed pulses (solid line) and calculated ray amplitude vs. travel time (vertical solid and dashed line) .

In Fig. 3 (the distance between the source and the receiver is about 312 km) the individual ray arrivals are not resolved. But the arrivals of the fours of rays can be reliably identified. In Fig.4 the result obtained at much shorter range (80 km) is presented. Here we can identify pairs of rays. In both cases the receiving hydrophone depth was 80 m.

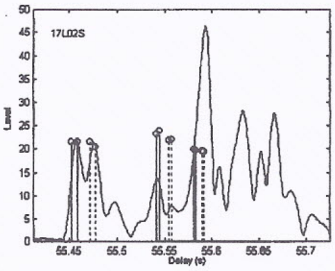

Fig. 4. Envelope of the compressed pulses (solid line) and calculated ray amplitude vs. travel time (vertical solid and dashed line) .

Fig. 5 (in this case the distance was equal 197 km, and the receiving hydrophone was located at the depth of 300 m) illustrates the situation when individual ray arrivals can be resolved.

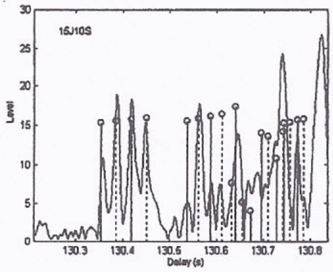

Fig. 5. Envelope of the compressed pulses (solid line) and calculated ray amplitude vs. travel time (vertical solid and dashed line) .

It should be pointed out that we theoretically calculated the travel time only of those rays which did not touch the bottom. The point is that the information about the bottom was rather poor and we could not calculate the ray reflected off the bottom with the necessary accuracy.

The above results show that individual ray arrivals are not resolved when the receiving hydrophone is located at a small depth. At the same time the arrivals of individual fours of ray can be resolved well. Their travel times can be used as the input parameters when solving different inverse problems of the acoustical monitoring.

The travel time of the fours of rays can be defined as a temporal coordinate of the "center of mass" of the peak formed by four unresolved pulses arrived to the hydrophone along the four corresponding ray paths. The drift causes the rather complicated problem of very precise measurements of distance variations and accounting this information in processing. The situation can be simplified if we use not absolute travel times but differences in travel times. The comparison of measured and theoretically predicted differences in ray travel times of the fours presented in Fig. 3 are shown in Fig. 6. In this Fig. 6 the differences in travel times are shown versus the numbers of fours corresponding to these differences.

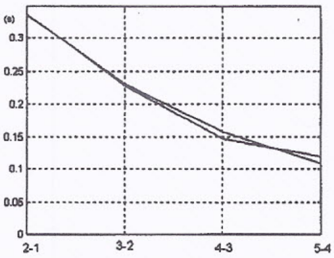

Fig. 6. The differences in travel times are shown versus the numbers of fours

The results presented above show that depending on depth of the drifting receiving hydrophone the identification of ray arrivals or fours of rays arrivals are possible. The measured differences in travel times are in good agreement with the theoretical predictions obtained using the ray code. This allows one to hope that differences in travel times registered from the drifting ship can be used as informative parameters when solving the problem of the acoustic monitoring of the temperature field inhomogeneities.

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