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RECONSTRUCTION OF VERTICAL DISTRIBUTIONS OF SOUND AND FLOW VELOCITIES AT STRONG OCEANIC CURRENTS VIA INVERSION OF ACOUSTIC TRAVEL TIMES

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Effect of strong ocean currents on sound propagation is simulated numerically in framework of ray acoustics. For acoustic remote sensing of sound speed and flow velocity a nonperturbative approach is proposed and implemented. Under environmental conditions typical to the Gulf Stream applicability of this approach is demonstrated.

L'influence du courant océanique fort a la propagation du son est reproduite numériquement par l'approximation de l'acoustique rayonnante. Pour le sentiment acoustique loign de la vitesse sonore et de la rapidité du flot l'approche nonperturbatrice est propos et réalisée. Sous les conditions de l'environnement typiques pour Gulf Stream l'applicabilité de cette approche est démontrée.

Tomographic mapping of ocean currents seems to be one of the most promising tools to study dynamics of the ocean [1-3]. This paper is a part of theoretical study of possibilities of acoustic monitoring of powerful oceanic flows from moving ships. Effect of strong current such as the Gulf Stream on acoustic signals propagating in opposite directions is estimated by numerical simulation in the framework of ray acoustic. Reconstruction of vertical distributions of sound and horizontal flow velocities by nonperturbative inversion of acoustic travel times is considered. Some properties of this solution are studied using simulated data. Environmental conditions close to that of the Gulf Stream are implied in all these calculations.

The influence of currents on the propagation of acoustic signals depends upon many factors and first of all upon the flow velocity u , which is typical for medium in hand. The most pronounced azimuth variations of acoustic fields appear to take place in the regions of powerful flows, like the Gulf Stream or the Kuroshio. Such a currents have sufficiently high flow velocity at the surface and intervening the ocean up to a large depth. To simulate all the effects induced by ocean currents one should certainly use computer code which makes it possible to calculate acoustic field in range-dependent moving media. However, if the source-receiver separation is not too large, adequate estimates can be obtained in the framework of the layered model of the ocean.

Departing from explicit integral expressions for eikonal, pressure amplitude at a ray and for its trajectory, an efficient computer code was developed by the authors to simulate high-frequency acoustic field in stratified moving media [4]. This code was applied to study a shift of convergence zone's boundaries induced by currents as well as differences in transmission loss and acoustic travel times in reciprocal transmission. For more details the reader is referred to [4].

The powerful currents turns out to exert an evident influence on the parameters of acoustic signals in the deep ocean, which is large enough to be measured using the modern experimental equipment. The vertical displacement of shadow zone's boundary

modern experimental equipment. The vertical displacement of shadow zone's boundary at fixed distance from the source amounts to 100-150 meters. The relative changes in the horizontal distance D from source to the beginning of first convergence zone approximately equals $\Delta D/D \approx |\Delta \bar{u}|/|\Delta c|$, where $\Delta \bar{u}$ and Δc are variations of sound and flow velocities respectively. For typical values $|\Delta c| = 50$ m/s, $|\bar{u}| = 1.5$ m/s and $D \approx 50$ km in accordance with this estimate the shift of convergence zone proved to be $\Delta D = 1.5$ -2 km. Due to this reason considerably acoustic reciprocity breaking may occur in the vicinity of shadow zone's boundaries. The difference in transmission loss with and against the current exceeds 15 dB in the frequency domain about 500 Hz. In the reciprocal tomography experiments data set consists of differential travel times ΔT . The flow velocity usually reaches its maximum values near the ocean surface. That's why the shadow turning rays have greater magnitudes of ΔT about 15-20 ms per cycle of ray.

Some of these results are illustrated by graphs of sound field intensities versus depth (Fig.1), calculated for signals propagating downstream (solid curve) and upstream (dashed curve). Profiles of sound speed c and flow velocity u , used in this simulation, are shown at Fig.1a. They correspond to CTD measurements during the survey of the Gulf Stream meander [5]. The point monopole source with frequency $f = 500$ Hz is situated at depth $z_s = 500$ m. The horizontal separation from the source equals $R = 58$ km. The absorption of sound was not taking into account. Surface and bottom assumed to be flat and perfectly reflecting. In this example the shadow zone's boundary passes at depth $z_p = 290$ m and $z_m = 220$ m for rays, propagating with and against the current. It results in large differences in acoustic intensity between these horizons, which amounts to 15 dB. These deviations are clearly observable in spite of presence of bottom reflected and surface reflected rays.

To simulate propagation of acoustic signals in moving ocean some approximate methods are widely used, which are based on substitution of real medium by a stationary one with some effective sound speed (ESS) depending on flow velocity [6-9]. Conditions of validity of such approximation was addressed in paper [4] using analytical comparison of exact and approximate solutions as well as numerical simulation. ESS was taken to be $c_e = c + \bar{u}$, where $\bar{u}$ is the projection of u on the vertical plane containing both source and receiver. It is shown that under conditions of guided propagation the main error in transmission loss is caused by errors in

phases of separate eigenrays $\delta\Phi = 2\pi f R O(|\bar{u}|^2 \chi^2 / c^2)$, accumulating with distance. Here R is source-receiver separation, f is the signal frequency and χ is the grazing angle of the ray involved. Bar denotes the average value along the ray path. The error grows with frequency f and distance R . This conclusion is in a good agreement with computer simulations. Let us consider Fig.2 for example. The vertical dependence of acoustic field intensity at the distance $R = 280$ km downstream was calculated with $f = 1$ kHz (Fig.2a) and $f = 5$ kHz (Fig.2b). Other conditions being equal to those of Fig.1. Solid curve and squares represent the acoustic pressure amplitude obtained via exact formulas of ray acoustic of moving media and within ESS approximation respectively. Discrepancies between these two graphs rises rapidly with frequency increase.

Determining sound speed c and current velocity u by means of ocean acoustic tomography implies solution of an inverse problem. This paper treats a kinematic inverse problem (KIP), where acoustic travel times T for various source-receiver separations are considered as input data.

If currents are slow, the inverse problem may be addressed via linear inversion [2]. However, linearization with respect to u isn't usually permissible, when sound propagates through powerful currents such as the Gulf Stream. Another approach, which was developed in paper [10], consists in generalizations of some results, obtained

earlier using Abel's transformation for media at rest, on moving media. The main advantage of our methods is their nonperturbative nature. That is, any reference profiles of c and u are not used during the inversion.

The inversion formulas mentioned above involve continuous data. It is of great importance for practical implementation, what amount of input information is really needed to find $c(z)$ and $u(z)$. This question is addressed at Fig.3. Original profiles

Fig.1. (a) The sound speed (1) and the flow velocity (2) vertical profiles. (b) Transmission loss vs depth at the distance $R=58$ km from the source.

Fig.2. Depth dependence of transmission loss obtained via exact formulas of ray acoustic and within ESS approximation. (a) $f=1$ kHz. (b) $f=5$ kHz.

c and u are just the same as on Fig.1a. Source and receiver are both at depth $z_s=680$ m. The problem consists in determining $c(z)$ and $u(z)$ above this horizon.

Input data (i.e. times of flight of all eigenrays) were calculated for source-receiver separations $x=iX_{\max}/N$, where $X_{\max}=15$ km is the distance from source to the boundary of shadow zone, $i=1,2,\dots,N$ and N is the number of points of measurements. Light circles, stars and squares stand for the difference between estimated and original profiles with $N=7$, $N=15$ and $N=20$ respectively. It turns out, that satisfactory accuracy of the inversion is presented even when the travel times between only 7 points are given. In practice, it is expedient to use the nonperturbative methods of inversion to obtain some initial estimate, of c and u vertical dependence, which can be refined, including determining c and u variability in horizontal plane, via standard linear inversion.

Fig.3. Influence of number of rays used on accuracy of inversion of $u(z)$ (a) and $c(z)$ (b).

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