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DYNAMIC HORIZONTAL WAVEGUIDES IN A SHALLOW WATER IN A PRESENCE OF SOLITON-LIKE INTERNAL WAVES

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In the paper the changing of the sound field structure conditioned by packets of internal solitons are considered within the framework of the theory "horizontal rays and vertical modes". It is ascertained, that the internal solitons can cause the "focusing" and "defocusing" of horizontal sound rays propagating at small angles to front of internal waves periodically in time. Such effect leads to the forming of "dynamic" horizontal sound channels and as result to the significant temporary fluctuations of acoustic signals on acoustic trace oriented along front of internal waves. The conditions of this effect are formulated in the paper. The numerical modeling approach, based on a parabolic approximation of sound field in horizontal plane and modal representation in vertical direction is developed in the paper to calculate field on an acoustic trace oriented along front of internal waves. The results presented in the paper can be used as basis for the remote monitoring of the characteristics of internal solitons packet in ocean shelf.

At the present period there is a considerable number of experimental data which prove out to permanent presence of internal waves packets in a diverse regions of ocean shelf (shallow water). The internal waves in packets are characterized by large amplitudes and short wave lengths. These packets are treated in ocean hydrodynamics as packets of internal solitons [1,2]. Internal solitons are one of basic reasons which causes significant perturbations of water layer stratification in shelf and as results leads to considerable fluctuations of acoustic signals propagating in shallow water.

In this paper we continue research of acoustic effects caused by internal solitons in shallow water. The acoustic effects conditioned by resonant sound scattering by internal solitons packets have been considered in [3]. This paper is concerned to theoretical research of possible formation of “dynamic” horizontal waveguides in shallow water due to internal solitons.

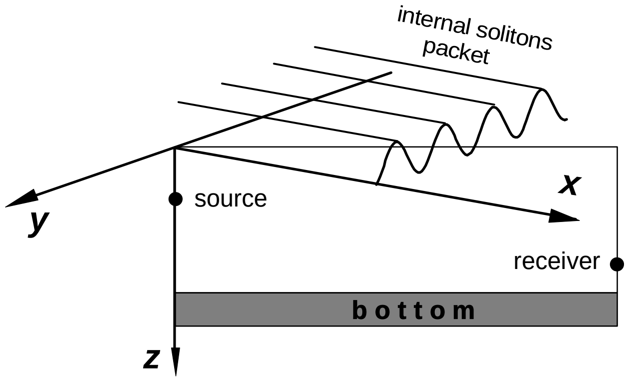

Figure1. Shallow water model

Shallow water model. Let us consider the 3-D shallow water waveguide in the Cartesian coordinates X, Y, Z (see. figure. 1). Waveguide consists of water layer with density $r_w(z)$ and squared refractive index: $n^2(z)+m(x,y,z,t)$. Here $n^2(z)$ (sound speed profile $c(z)$) cîrresponds to stratification of water layer non perturbed by soliton-like internal waves, $m(x,y,z,t)$ - perturbation caused by internal waves. We suppose that water layer is limited by free surface $z=0$ and homogeneous absorbing half-space $z=H$. Let the bottom be characterized by density r_1 and squared refractive index: $n_1^2(1+ia)$, where a is determined by bottom absorption.

Perturbation $m(\vec{r},z,t)$ is determined by parameters of internal waves:

$$m(\vec{r},z,t) = -\frac{2dc(\vec{r},z,t)}{c(z)} = -2QN^2(z)z\,(\vec{r},z,t) \qquad (1)$$

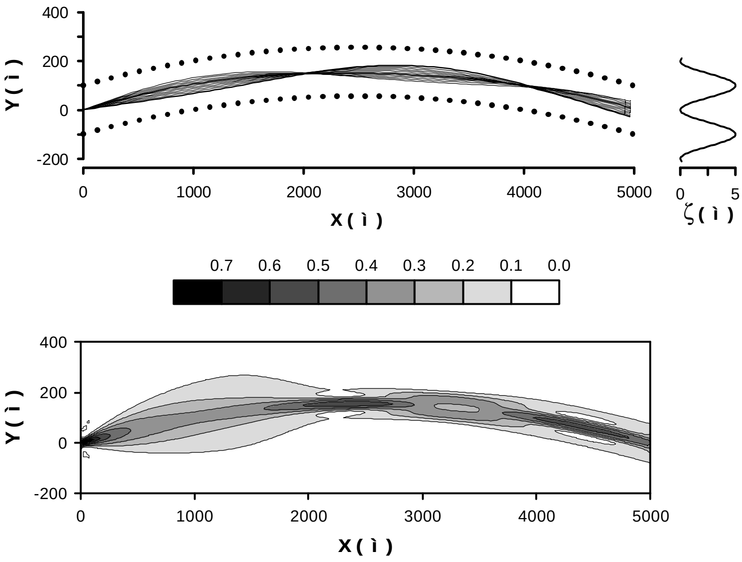

Figure 3

where dc - perturbation of sound speed caused by displacement of water layers with constant density, $N(z) = \left(gr^{-1}\, dr/dz\right)^{1/2}$ - buoyancy frequency defined by water layer density as function of depth, r - water density, g - gravity acceleration; $Q \approx 2.4\ \tilde{n}^2/\grave{\imath}$, $\vec{r} = (x, y)$ - radius-vector in horizontal plane, z - vertical displacement of surface of water layers. According to [2,3] the vertical displacement can be written as:

$$z\,(\vec{r}, z, t) = \Phi(z) z_s(\vec{r} - \vec{u}t)$$

where $\vec{u} = (u_x, u_y)$ - velocity of soliton-like internal waves in horizontal direction, Φ - first gravity mode normalized by its maximal value ($\max \Phi(z) = 1$)

<u>Horizontal dynamic waveguid</u>. Within the framework of the theory "horizontal rays and vertical modes" point source $(0, z_0)$ sound field observed in the point $(\vec{r}, z)$ is determined by the following expression:

$$\Psi(\vec{r}, z) = \sum_n \sum_m A_{nm}(\vec{r}) y$$

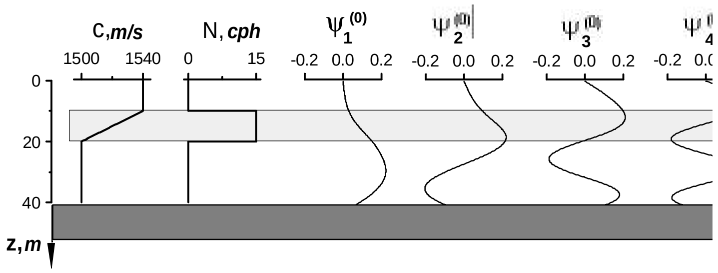

Figure 2. Water stratification

Here $A_{nm}(x, y)$, $q_{nm}(x, y)$ - amplitude and phase relating to acoustic mode $y_m(x, y, z)$. Due to for each vertical mode some number of horizontal rays can be found, vertical mode (index m) and horizontal rays (index n).are summarized in the expression (3).

The ray track $\vec{r}_{nm}(s)$ with number n and relating to mode m is determined by the following differential equations:

$$d\vec{r}_{nm}/ds = \vec{t}_{nm}, \qquad d\vec{t}_{nm}/ds = q_m^{-1} \nabla_\perp q_m(\vec{r}), \tag{4}$$

where $ds = \sqrt{(dx)^2 + (dy)^2}$, $\vec{t}$ - unit vector tangent to ray track, $\nabla_\perp$ - gradient in direction across ray track. One can see from (9) that real part of modal wave number $q_m(x, y)$ can be considered as value for horizontal rays relating to mode with number m.

<u>Sound field modeling on acoustic trace along internal wave front</u>. Let us consider the method of sound field modeling on acoustic trace along internal waves front. It is undoubtedly that in this case the sound field can be simulated on the basis of the mentioned above theory "horizontal rays and vertical modes" by summarizing of amplitudes corresponding to various horizontal rays arrived at receiver point. However, in our opinion the approach based on the a parabolic approximation sound field in horizontal plane and modal description in vertical direction is more suitable to such kind of modeling. That is because the using of parabolic approximation allows us to avoid well-known difficulties of geometrical acoustics: caustics, turn points and so on.

We will use curvilinear coordinates for the sound field simulating in case under review. Let us consider sound field in coordinates t , h , where t is coordinate along the front of internal waves and

h - across one. In our approach sound field is presented by the following sum:

$$\Psi(t,h,z)=\sum_{n=0}^{N}F_n(t,h)\psi_n(t,h;z)\exp\left[iq_n^{(0)}t\right], \qquad (5)$$

where $F_n(t,h)$ - modal amplitude changed as function ÿâëÿåòñÿ ìåäëåííî ìåíÿþùåéñÿ - ôóíêöèåé ïðîäîëüíîé êîîðäèíàòû t . In forward scattering approximation $F_n(t,h)$ parabolic equation:

$$\frac{\partial F_n}{\partial t}=\frac{i}{2q_n^{(0)}}\frac{h_t}{h_h}\frac{\partial}{\partial h}\left(\frac{h_t}{h_h}\frac{\partial F_n}{\partial h}\right)+\frac{iq_n^{(0)}}{2}\left(h_t^2 n_n^2-1\right)F_n, \qquad (6)$$

where $n_q(t,h)=q_n(t,h)/q_n^{(0)}$ can be considered as refractive index, corresponding to mode with number n . The standard scheme (well-known as SSF: Slip Step Fourier algorithm [4]) of numerical solving is applied in work to find the modal amplitude.

Results of sound field modeling within the framework of the approach mentioned above are presented on the figures 3 and 4. The horizontal distribution of value:

$$\left|F_3(x,y)\right|^2/\left|F_3(0,0)\right|^2, \quad (7)$$

i.e. modal energy normalized by maximum are shown on these figures for mode number 3 .

The results shown on these figures correspond to vertical stratification of water layer corresponding to the one shown on the figure 1, sound frequency $f=250$ Ãö , parameter of source function $q_{\max}=p/18$

Figure 3 corresponds to the case when source is located in the horizontal “dynamic” channel (i.e. between crests of adjacent solitons). The figure 4 demonstrates inverse case when source is located between adjacent horizontal channels (i.e. on the crests of the internal soliton).

One can see that there is a good accordance between tracks of modal rays obtained by solving (4) and distribution of modal energy, determined by parabolic equation (6). Corresponding to calculations results presented on the figures 3 and 4 the fluctuations of sound intensity caused by internal soliton crossing acoustic trace can achieve the values about 6 - 3 dB. Maximal value (6 dB) of intensity fluctuations is observed when source and receiver are located on the axis of horizontal channel (i.e. on the same internal soliton crest). It should be noted that sound fluctuations in receiver point due to internal solitons packets and horizontal motion of these packets are synchronous in time. Therefore time interval of these intensity fluctuations can be estimated by relation between internal soliton width and its speed Λ/u . In case under review this estimation gives value about $\approx$200 seconds

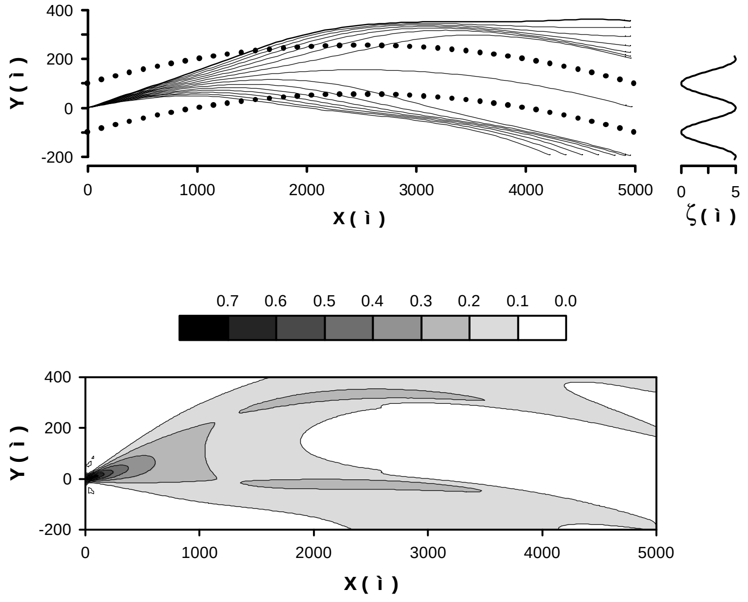

Figure 4

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