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ACOUSTIC FIELD IN SHALLOW WATER AT PRESENCE OF INTERNAL SOLITONS

Boris Katsnelson, Sergey Pereselkov
394693 Russia, Voronezh, University Square, 1
E-mail: katz@mph.vsu.ru, sap@saper.vsu.ru

In the paper the transformations of sound field structure conditioned by packets of internal solitons (IS) are considered within the framework of the theory "horizontal rays and vertical modes". We analyze a two cases of the acoustic trace orientation in relation to front of IS. It is shown that acoustic effects have resonant frequency dependence when internal solitons propagate along trace. It is ascertained as well, that the IS can lead to formation of "dynamic" horizontal sound channels and as result the significant temporary fluctuations of acoustic signals will be 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 in ocean shelf.

INTRODUCTION

At the present period there are a great number of experimental data which prove out to permanent presence of packets of intensive internal waves 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 major reasons which causes significant perturbations of water layer stratification in shelf and as results lead to considerable fluctuations of acoustic signals propagating in shallow water. These acoustic effects due to IS can be used as basis of diverse methods of remote sensing of this hydrodynamic phenomenon. In this paper we consider particularities of acoustic effects caused by internal solitons in shallow water. The acoustic effects under review are conditioned by both resonant sound scattering by internal solitons packets and formation of "dynamic" horizontal sound channel in shallow water in presence of internal solitons.

1. SHALLOW WATER MODEL

Let us consider the shallow water as 3-D hydroacoustic waveguide in the Cartesian coordinates X, Y, Z (see fig.1). Waveguide consists of water layer with density $\rho_w(z)$ and square of refractive index: $n^2(z)+\mu(x,y,z,t)$. Here $n^2(z)$ is corespondent to stratification of water layer non perturbed by IS (corresponding sound speed profile is denoted by $c(z)$), $\mu(x,y,z,t)$ - perturbation of the layer stratification caused by internal waves. We suppose that water layer is limited on depth by free surface $z=0$ and homogeneous absorbing half-space - bottom $z=H$. The bottom be characterized by density ρ_1 and square of refractive index: $n_1^2(1+i\alpha)$, where α is determined by bottom absorption.

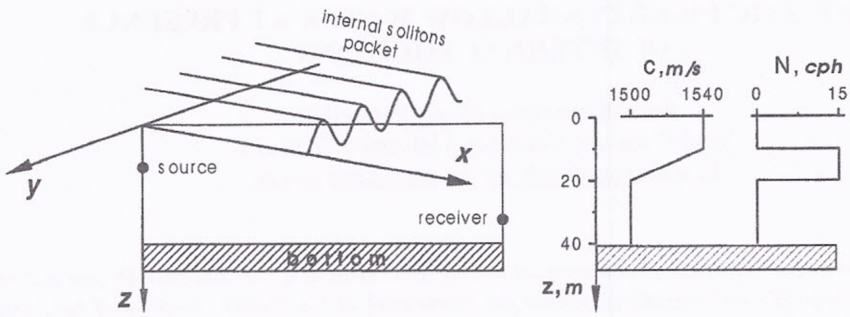

FIGURE 1. Shallow water model

As known the perturbation of layer stratification $\mu(\vec{r},z,t)$ is determined by parameters of internal waves:

$$\mu(\vec{r},z,t) = -\frac{2\delta c(\vec{r},z,t)}{c(z)} = -2QN^2(z)\zeta(\vec{r},z,t) \tag{1}$$

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

$$\zeta(\vec{r},z,t) = \Phi(z)\zeta_s(\vec{r}-\vec{u}t) \tag{2}$$

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

2. INTERNAL SOLITONS PROPAGATING ALONG ACOUSTIC TRACE.

Let us consider case when soliton packets propagate approximately along acoustic trace i.e. angle θ between trace and direction of solitons spreading is small enough. The sound field on such acoustic trace may be presented as sum of acoustic modes $\varphi_n(z)$ with a random modal coefficients $c_n(r)$:

$$\psi(r,z) = \sum_n \frac{c_n(r)}{\sqrt{\beta_n r}}\varphi_n(z)\exp(i\beta_n r), \tag{3}$$

where, $\xi_n = \beta_n + i\gamma_n/2$ are modal wavenumbers. Within framework of the statistical approach such as in works [3] can be obtained the modal distribution of the full sound field intensity $I_f(r,z) = \overline{\left\langle |\psi(r,z)|^2 \right\rangle}$. Here brackets and top line denotes the range averaging over samples of realization and over horizontal interval longer than $L_{\text{int}} = 2\pi/\min|\beta_n - \beta_m|$ correspondingly. One can derive that the coefficient of modes interaction a_{nm} depends upon the value of the solitons packets spectrum $S(\sigma)$ at $\sigma = |\beta_n - \beta_m|/\cos(\theta)$ i.e.:

$$a_{nm} \sim S(|\beta_n - \beta_m|/\cos(\theta)). \tag{4}$$

According to experimental data the packet spectrum $S(\sigma)$ has complex form but it is narrow enough. That is why for packet spectrum we use the following expression as the first approximation:

$$S(\sigma) \sim \exp\left(-(\sigma - \sigma_p)^2/2\Delta^2\right) \tag{5}$$

where spectrum parameter $\Delta \sim 0.1\sigma_p << \sigma_p = 2\pi/\Lambda_p$. The packet quasiperiod Λ_p is about $100 - 400\, m$, and amplitudes of IS is about $5 - 10\, m$.

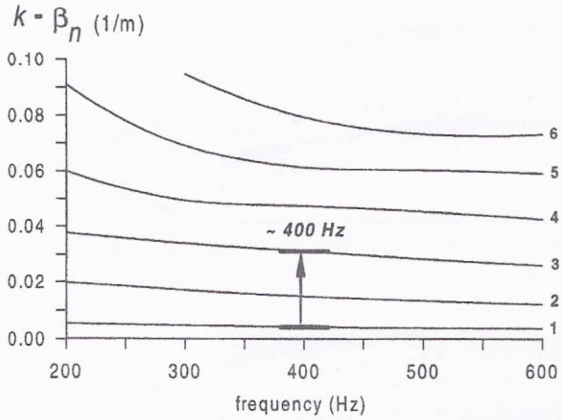

FIGURE 2. Frequency dependence of modal wavenumbers.

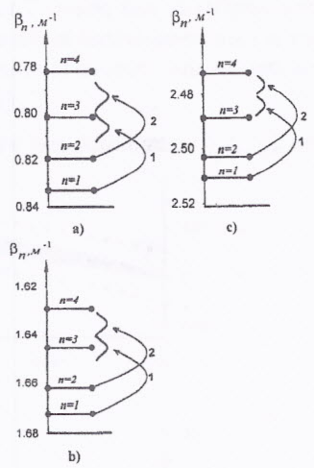

FIGURE 3. Modal spectrum for diverse frequency: a) $f = 200Hz$, b) $f = 400Hz$, c) $f = 600Hz$.

The dependence (5) is similar to the Bragg condition in the theory of scattering. The expression (5) is basic dependence explaining the resonance-like behavior of the acoustics effects caused by IS. Assuming that the width of the packets spectrum is Δ the condition of the resonant scattering for modes with indexes n, m may be written as:

$$\sigma_p - \Delta \le |\beta_m - \beta_n|/\cos(\theta) \le \sigma_p + \Delta \tag{6}$$

In this case $a_{nm} \neq 0$. Thus scattering by packets leads to decreasing of the coherent component intensity in modes n, m and redistribution of the full sound intensity between modes n, m. In real situation the packet spectrum $S(\sigma)$ is narrow enough. In turn the spectrum of the modal wavenumbers is rare enough for low-frequency sound. That is why for some sound frequencies there is no any pair of modes satisfying to (6) (see figure 2 and 3 a) $f = 200Hz$ c) $f = 600Hz$). As result the sound scattering by packets is negligible for these sound frequencies. But if there exists a pair of modes satisfying to (6) (see figure 3 b) $f = 400Hz$) then the sound scattering becomes significant.

3. INTERNAL SOLITONS PROPAGATING ACROSS ACOUSTIC TRACE.

Lets us consider case when acoustic trace is oriented along front of internal solitons. 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 [3]:

$$\Psi(\vec{r},z) = \sum_n \sum_m A_{nm}(\vec{r}) \psi_m(\vec{r},z) \exp[i\theta_{nm}(\vec{r})] \qquad (7)$$

Here $A_{nm}(x,y)$, $\theta_{nm}(x,y)$ - amplitude and phase relating to acoustic mode $\psi_m(x,y,z)$. It should be noted that not one but several rays corresponding to same mode can arrive in receiver point in general. These rays have diverse track and therefore they have diverse amplitude and phase. That is why both vertical mode (index m) and horizontal rays (index n).are summarized in the expression (7).
Let us assume that front of internal soliton is crooked (radius of curvature - R):

$$\zeta_s(\vec{r} - \vec{u}t) = 0.5\zeta_0 \{\cos[2\pi(r - r_0)/\Lambda_p] + 1\}, \qquad (8)$$

where ζ_0, Λ_p - amplitude and width of internal solitons ($\Lambda_p \ll R$).

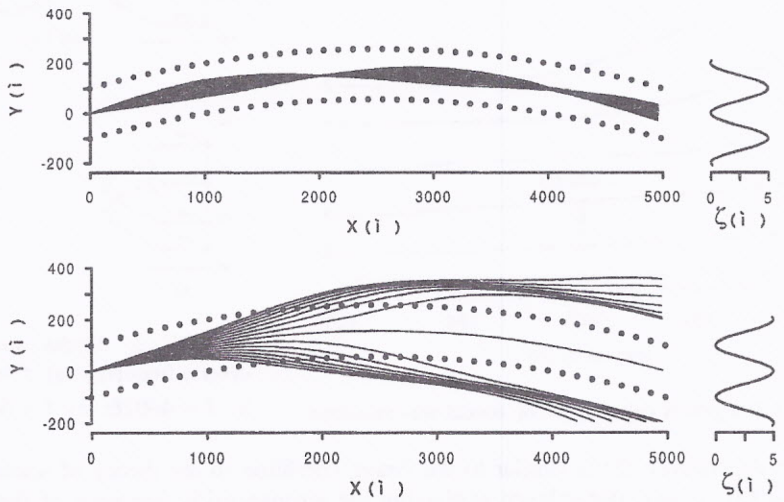

FIGURE 4. Rays tracks in horizontal plane: ***focusing*** and ***defocusing***.

The structure of sound rays in horizontal plane depends upon r_0 i.e. internal solitons position in relation to acoustic trace. If packet of internal solitons is out trace then rays are straight lines corresponding to cylindrical spreading. If acoustic trace in internal solitons then two contrary behaviours of sound rays in horizontal plane can be observed. In the case of source position in the area of local maximum $\zeta_s = \zeta_0$ of vertical displacements due to internal soliton (peak of soliton) we will observe the horizontal sound rays defocused along internal wave front passed through source. In the case of source position in the area of local minimum $\zeta_s = 0$ of vertical displacements due to internal soliton (between adjacent peaks of soliton) we will observe the horizontal sound rays focused along internal wave front passed through source. Both of these cases are shown in the figure 4. One can see, that upper figure corresponds to sound rays in horizontal channel. The under figure corresponds to contrary situation.

It should be emphasized that while spreading of internal solitons the focusing or defocusing of acoustics intensity in horizontal plane are observed for all acoustic modes at the same time. It leads to significant increasing of the effect under consider in the case of multi-modal acoustic field.

For the computing of sound field we use parabolic approximation sound field in horizontal plane and modal description in vertical direction. The curvilinear coordinates in horizontal plane are more fit into sound field simulating in case under review. Let us consider sound field in coordinates τ , η, where τ is coordinate along front of internal waves and η - across one. In our approach sound field is presented by the following sum:

$$\Psi(\tau,\eta,z) = \sum_{n=0}^{N} F_n(\tau,\eta)\psi_n(\tau,\eta;z)\exp\left[iq_n^{(0)}\tau\right], \qquad (9)$$

where $F_n(\tau,\eta)$ - modal amplitude which is slowly varied as function of coordinate . In forward scattering approximation $F_n(\tau,\eta)$ is determined by the following parabolic equation:

$$\frac{\partial F_n}{\partial \tau} = \frac{i}{2q_n^{(0)}}\frac{h_\tau}{h_\eta}\frac{\partial}{\partial \eta}\left(\frac{h_\tau}{h_\eta}\frac{\partial F_n}{\partial \eta}\right) + \frac{iq_n^{(0)}}{2}\left(h_\tau^2 n_n^2 - 1\right)F_n, \qquad (10)$$

where $n_q(\tau,\eta) = q_n(\tau,\eta)/q_n^{(0)}$ can be considered as refractive index, corresponding to mode with number . The standard scheme (well-known as SSF: Slip Step Fourier algorithm [6]) 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 in the figure 5. The horizontal distribution of value:

$$\left|F_3(x,y)/F_3(0,0)\right|^2, \qquad (11)$$

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

The upper figure corresponds to the case when source is located in the horizontal «dynamic» channel (i.e. between crests of adjacent solitons). The lower figure 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 and distribution of modal energy, determined by parabolic equation. Corresponding to calculations results presented in the figure 5 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 sound intensity fluctuations can be estimated by relation between internal soliton width and its speed Λ_p/u. In case under review this estimation gives value about □200 seconds

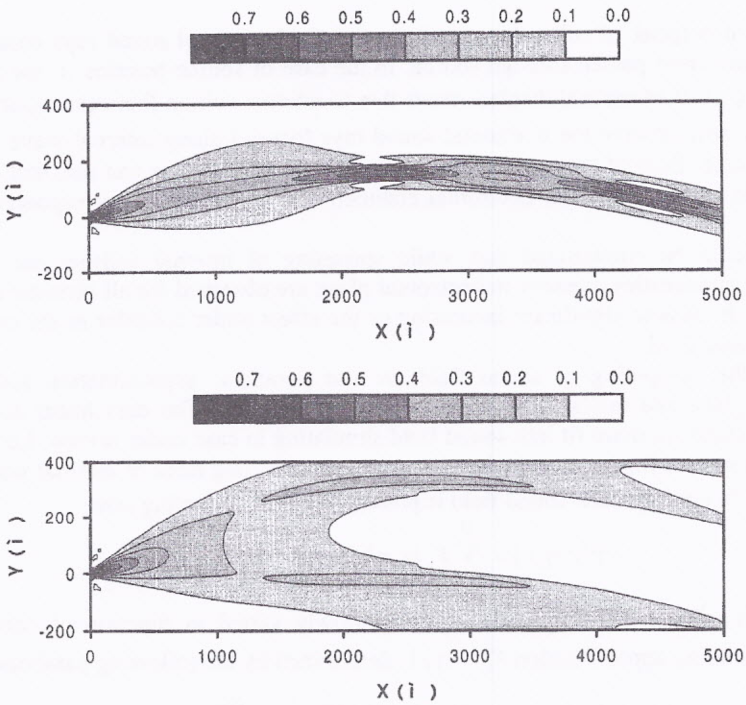

FIGURE 5 Distribution of modal intensity in horizontal plane: ***focusing*** and ***defocusing***.

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