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Influence of Seasonal Changes of Hydrological Conditions on the Ambient Sea Noise Field in the Baltic Sea

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Based on the data concerning the sound speed profiles in the Southern Baltic Sea, calculations of vertical directionality of the ambient-sea-noise field have been performed.
The changes of vertical directionality function and intensity of the ambient-sea-noise are analysed for different points in the area. The seasonal and diurnal changes of the noise intensity and directionality are also analysed.

1. Introduction

The knowledge of an ambient sea noise characteristics is necessary in numerous practical applications. The ambient noise field in shallow water is complicated by the multiple interactions of the sound generated at the surface with the sea bottom and dispersed inhomogeneities. Also, refraction plays significant role at local noise level. The analysis of the ambient noise directionality had been introduced by Urick [8], and Talham [9] who applied a simple ray model with the noise sources distributed uniformly over the whole sea surface. Also, wave methods for a case of low frequencies and shallow sea were introduced [1]. Urick [8] assuming a homogeneous water column had found that the noise spectrum was not dependent of the depth. The problem of equivalency between the observed in the sea the ambient noise spectrum and the spectrum of noise surface sources in the typical for the Baltic sea propagation conditions was analysed [7] using ray models. It was found that due to frequency dependent bottom absorption, the observed spectrum of the ambient noise could be different from the original sources spectrum.
Varying the sound speed profile, calculations of seasonal changes of the ambient sea noise vertical directionality and the noise level in the Baltic Sea were also investigated [6].

The presented model, however made in ray approximation, involves the analysis of a more complete and improved model of sea environment including the role of the scattering layers and scattering at the bottom inhomogeneities.

The work continues a long line of earlier investigations not cited here, performed from the early 60's [2,9] up to models of ambient sea field in works of Covley, Holden, Harrison, and Harrison, Covley [3,4}.

2. Baltic environmental conditions

2.1. The Baltic Sea climatology

The basic pattern of water masses in the Baltic Sea is well understood and the origin of water types has been identified in details. A prominent feature of the South Baltic Sea deep basins is the existence of the two distinct water masses - the true Baltic water overlaying the water mass of the North Sea origin. Between the two types, at the depth of 40-70 metres there is observed a permanent mixing zone (halocline). This relatively simple picture of the Baltic Sea interior, is complicated by a seasonal heat influx which forms a sharp thermocline at the depths 20-40 m. In summer time, there is three-layer sandwich-like structure with the warm summer Baltic water in the upper mixing layer, above the cold Baltic water having been formed in the winter season overlying the deep North Sea water. The temperature and salinity of the North Sea water are higher as in the above lying layers. The presence of the winter layer causes a sound speed minimum and forms a deep acoustic duct in the 20 meters of water thickness. Nevertheless, in the whole water column the summer sound-speed profile resulted in downward refracting energy. In the winter season a subsurface acoustic duct is formed. Figure 1 shows the seasonal changes pattern of a sound speed profiles typical of the south Baltic Sea. Approximation of the sound speed profile in the model was performed using layers with a linear gradient.

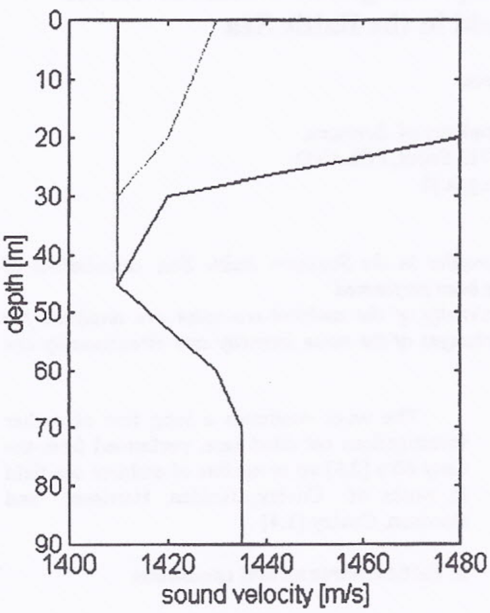

Fig.1. Typical changes of sound speed profiles in the Southern Baltic Sea Deeps through the year.

2.2. Scattering layers

The classical oceanic deep scattering layers are not characteristic of the shallow Baltic Sea. However, in some seasons there persist dense aggregations of small marine organisms. The maximum density is reached in the late summer season, at nights, when many zooplankters tend to aggregate at the density interface, at the base of the upper mixed layer and disappear at sunrise. The temporal variations in the propagation conditions caused by dense scattering layers may lead to substantial transformation of the arrival structure of the noise.

2.3. Bottom properties

The Baltic Sea is a typical example of a shallow sea with complicated stratigraphy of the bottom and mixed types of sediments. Because of the presence of very different materials from mud to bedrock, and sometimes the "exotic" for a sea bottom, such as peat and gaseous semi-liquid mud the horizontal scale of sediments homogeneity varies from about 1 kilometre to tens of kilometres. In the areas of the Baltic Deeps (Gdansk. Bornholm, Arkona basins), water and gas saturated organic silt and silty clay with the thickness up to 20-25 m prevails. The whole layer of unconsolidated saturated sediments is transparent for an incident low frequency sound with typical attenuation of the order of 0.01 dB/m/kHz. The sound speed in the sediments shows a value ranging between 1300 and 1500 m/s [5]. However, in some cases, the value of sound speed could drop down to 300 m/s in gaseous organic sediments. The low attenuation makes the sound penetrate deep into the bottom. The sound speed gradients in the upper sediment layers can be both negative and positive, but in the deeper layers they are usually positive so the acoustic energy of the noise field refracts back into the water.

3. The ambient sea noise model

Let us consider the problem in the geometric acoustic approximation in the range independent environment. The noise intensity arriving straight from noise sources uniformly distributed at the sea surface, to the observation point, at a graze angle α, can be expressed in the form

$$dI_1(\alpha,f) = \frac{W(f)\,df\;G^2(\alpha)\,c_0^2\cos\alpha\;d\alpha\;\exp(-2\beta(f)\,R)}{\int_0^{\pi/2} G^2(\alpha_0)\cos\alpha_0\;d\alpha_0\;c^2\sqrt{1-\left(\frac{c_0}{c}\cos\alpha\right)^2}} \qquad (1)$$

where - $W(f)$ – spectral density of noise sources from a unit surface

α_0 – grazing angle from the sea surface,

$G(\alpha_0)$ – directionality function of noise sources distributed inside of thin subsurface layer was proposed in the form $G(\alpha_0)=\sin^m(\alpha_0)$, where value of $m \cong 2$ reflected dipole character of the noise sources collected close to the sea surface,

c_0 – sound speed in the subsurface water layer,

$c = c(z)$ - sound speed at the depth of z,

$\beta(f)$ - pressure attenuation coefficient in the sea water in [nep/m],

R – path length of the ray from the surface element to the observation point,

α - angle between the horizon and the ray at the depth z at the observation level.
In case of the shallow water conditions, there are multiple reflections between the sea surface and the bottom which increases the noise level and changes the directionality. We obtain the noise intensity summing up intensities from lower and upper hemisphere and a sum of geometric series appear with effective coefficients of reflection on the boundaries.

The intensity depends not only on the local wind speed but also on the season (the water temperature profile), a bottom type, and an area depth. Temporal variations in the propagation conditions caused by internal waves and migrating or gathering organisms may lead to substantial transformation of the arrival structure of the noise. If we perform suitable approximation, placing segments instead of arcs along a path of rays, in case of an acoustically hard bottom, the model reduces to relatively simple formulas. They are associated with different seasons and the depth of observation points. In case of partly penetrable isovelocity bottom in the wintertime, for the point situated above the halocline, we receive a directionality function in a simplified form as:

for upper hemisphere for rays reflected at the bottom

$$g_1(\alpha^+,z)=\frac{\sin^{2m-1}(\alpha)\exp\{-2\beta(f)z/\sin[(\alpha+\alpha_B)/2]\}}{1-\exp\{-4\beta(f)H/\sin[(\alpha+\alpha_B)/2]\}V_S^2(\alpha)V_B^2(\alpha_B,f)} \tag{2a}$$

and for rays bounding in the halocline

$$g_1(\alpha^+,z)=\frac{\sin^{2m-1}(\alpha)\exp\{-2\beta(f)z/\sin(\alpha)\}}{1-\exp\{-4\beta(f)(z_{max}+z)/\sin[(\alpha+\alpha_B)/2]\}V_S^2(\alpha)} \tag{2 b}$$

For lower hemisphere, we have analog formulas

$$g_1(\alpha^-,z)=\frac{\sin^{2m-1}(\alpha)\exp\{-2\beta(f)(z_{max}+z)/\sin(\alpha)\}}{1-\exp\{-4\beta(f)(z_{max}+z)/\sin[(\alpha+\alpha_B)/2]\}V_S^2(\alpha)} \tag{3a}$$

$$g_1(\alpha^-,z)=\frac{\sin^{2m-1}(\alpha)\exp\{-2\beta(f)(2H-z)/\sin[(\alpha+\alpha_B)/2]\}V_B^2(\alpha_B,f)}{1-\exp\{-4\beta(f)H/\sin[(\alpha+\alpha_B)/2]\}V_S^2(\alpha)V_B^2(\alpha_B,f)} \tag{3b}$$

where - H – the sea depth,

α_B- bottom grazing angle of the ray received at the depth of z, at α,

$V_S(\alpha)$ – scattering coefficient at the sea surface,

$V_B(\alpha_B,f)$ – scattering coefficient at the bottom, a function of both incident angle and frequency

z_{max} - turning point depth for a ray received at α.

At a point situated below the halocline the directionality could be expressed in form

For the rays received from the upper hemisphere we obtain

$$g_1(\alpha^+,z)=\left[1-\left(\frac{c_0}{c_H}\right)^2\cos^2\alpha\right]^{\frac{2m-1}{2}}\frac{\exp\{-2\beta(f)z/\sin[(\alpha+\alpha_B)/2]\}}{1-\exp\{-4\beta(f)H/\sin[(\alpha+\alpha_B)/2]\}V_S^2(\alpha)V_B^2(\alpha_B,f)} \tag{4}$$

and for lower hemisphere

$$g_1(\alpha^-,z)=\left[1-\left(\frac{c_0}{c_H}\right)^2\cos^2\alpha\right]^{\frac{2m-1}{2}}\frac{\exp\{-2\beta(f)(2H-z)/\sin[(\alpha+\alpha_0)/2]\}V_B^2(\alpha_B,f)}{1-\exp\{-4\beta(f)H/\sin[(\alpha+\alpha_B)/2]\}V_S^2(\alpha_0)V_B^2(\alpha_B,f)} \tag{5}$$

where C_H – the sound speed in water near the bottom

C_0- the sound speed in the surficial water.

For the summer period for a point placed at the depth z near the axis of the deep water acoustical channel we receive

$$g_5(\alpha^+,z)=\left[1-\left(\frac{c_0}{c_Z}\right)^2\cos^2\alpha\right]^{\frac{2m-1}{2}}\frac{\exp\{-2\beta(f)z/\sin[(\alpha_0+\alpha_B)/2]\}}{1-\exp\{-4\beta(f)H/\sin[(\alpha_0+\alpha_B)/2]\}V_S^2(\alpha_0)V_B^2(\alpha_B,f)} \quad (7)$$

$$g_5(\alpha^-,z)=\left[1-\left(\frac{c_0}{c_Z}\right)^2\cos^2\alpha\right]^{\frac{2m-1}{2}}\frac{\exp\{-2\beta(f)(2H-z)/\sin[(\alpha_0+\alpha_B)/2]\}V_B^2(\alpha_B,f)}{1-\exp\{-4\beta(f)H/\sin[(\alpha_0+\alpha_B)/2]\}V_S^2(\alpha_0)V_B^2(\alpha_B,f)} \quad (8)$$

where $\alpha_0 = \arccos\left(\frac{c_0}{c_Z}\cos\alpha\right), \alpha_B = \arccos\left(\frac{c_B}{c_Z}\cos\alpha\right)$

After establishing the simple, but unrealistic for the Baltic deeps model, including the sound reflection at the water-sediment interface only, the similar to above presented algorithm have been introduced incorporating the transmission into sediments layer. The sound speed profile in the sub-seafloor layer of the liqud sediments is aproximated as a linearly increasing sound speed with the constant density and absorption. A supporting solid bottom forms an isotropic semispace. The reflection-transmission coefficients at the flat boundaries have been taken according to the modified Rayleigh formula [9].

4. Some results of numerical modelling.

A good illustration of the changes of the directionality influenced by seasonal rising of temperature in the subsurface water are presented in Figs. 2 and 3. We have examined it using four-layer model of temperature and salinity with the sound speed profiles as in Fig.1. Examples of the changes of ambient sea noise directionality function during winter-spring season, at a point placed at the depth of z=35 m are displayed in Figure 2. The sound speed values in the upper mixed water layer have been increasing from 1390 m/s (winter) to 1430 m/s (spring situation).

The following set of parameters of the fluid like bottom has been chosen:
the densities of the sediment and the water $\rho_S/\rho_W = 1.008$, the sound speed in the near-bottom water c_H=1535 m/s, the compressional sound speed in sediments at the water-bottom interface $c_B=1.06 * c_H$, gradient of sound speed in fluid sediments γ =+0.5 1/s, fluid sediments layer thickness 30 m, coefficient of attenuation in the fluid sediments α_B=0.01 dB/m/kHz. The sea depth H=90 m. Here the noise frequency is equal to f=2000 Hz. The directionality function at lower frequencies has a local minimum for the grazing angles near 90 degree. When we are moving to higher frequencies, the usual maximum in the noise directionality function appears around the upward direction. This phenomenon could be explained that any noise entering the fluid sediments at relatively small grazing angles will have tendency to return to the water column. Rays striking the hard bottom almost vertically are transmitted into deeper layers and attenuated there.

An example of evolving of the ambient sea noise directionality function during increase of the surficial water temperature at a spring-summer season is shown in Fig. 3.

As in the previous case the observation point is situated at the depth of 35 m. The sound speed values in the upper mixed water layer are changing from 1435 m/s (spring) to 1490 m/s (summer). At this time in the Baltic sea the deep water sound channel is formed with downward – refracting propagation conditions. At the point situated in the channel the notch in the directionality function around horizontal rays comes up, especially in the high frequency range.

Due to seasonal variations in the sound-speed structure the propagation conditions in the Baltic sea are strongly influenced by bottom losses. There is fever less bottom interactions in a winter period than in the summer one, which gives higher level of the ambient noise. The next Figure 4 gives examples of the seasonal variability of the noise intensity at two different frequencies during the year.

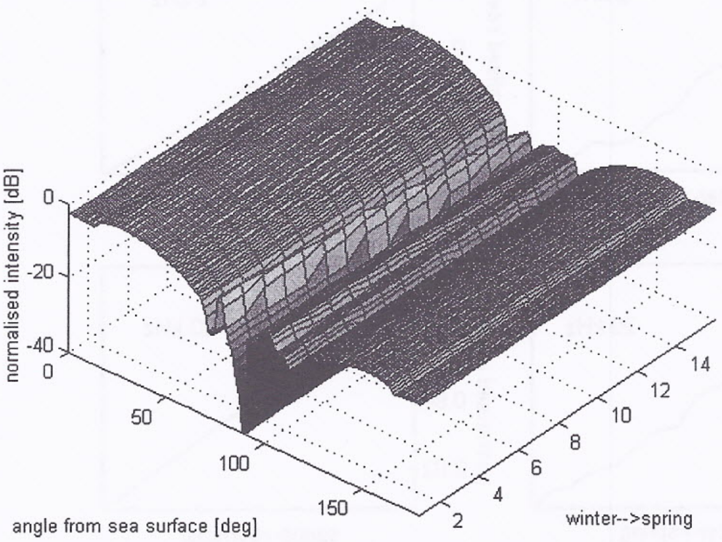

Fig. 2. The evolution of the ambient sea noise directionality function in the Southern Baltic sea area, from winter to spring seasons, at the observation point depth z=35 m and at the low frequency of f=2000 Hz. The sound speed values in the upper mixed water layer increase from 1390 m/s (winter) to 1430 m/s (spring situation).

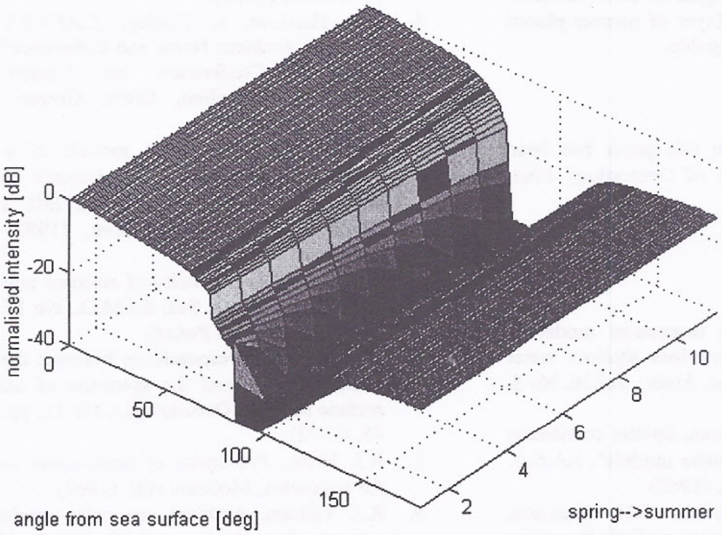

Fig. 3. Calculated evolution of the ambient sea noise directionality function in the Southern Baltic sea area, from spring to summer, the observation point placed inside the Baltic deep water acoustic channel, at the high frequency of f=20000 Hz. The sound speed values in the upper mixed water layer are changing from 1435 m/s (spring) to 1490 m/s (summer).

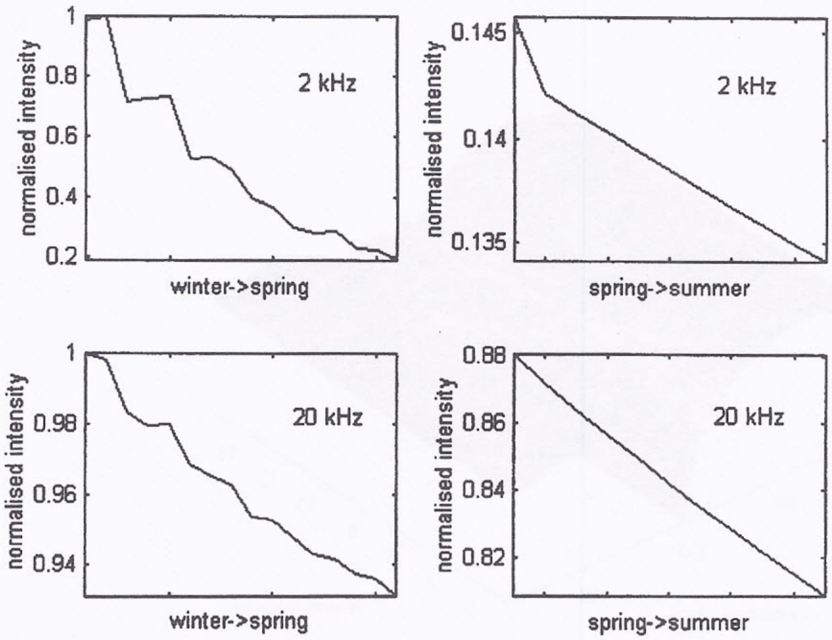

Fig.4. The seasonal changes of the noise intensity during the year at different frequencies, at 2 kHz in the upper part and at 20 kHz at the bottom part of the figure.

The effect of volume scattering of noise upon the dense scattering layers at nights could be compare to the input of additional layer of sources placed inside the deep water waveguide.

5. Acknowledgements

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