NONLINEAR ACOUSTICAL METHODS IN THE DETECTION OF GASSY SEDIMENTS IN THE GULF OF GDAŃSK

JAROSŁAW TĘGOWSKI[a], JAROMIR JAKACKI[b], ZYGMUNT KLUSEK[a], STANISŁAW RUDOWSKI[c]

[a]Institute of Oceanology, Polish Academy of Sciences
Powstancow Warszawy 55, 81-712 Sopot, Poland
tegowski@iopan.gda.pl
[b]Naval Postgraduate School,
833 Dyer Road, Monterey, USA, CA 93943
[c]Institute of Oceanography, University of Gdansk,
Al. Marszałka Piłsudskiego 46, 81-378 Gdynia, Poland

The application of nonlinear backscattering of acoustical signals in detection of gas bubbles in subsurface layer of sediment of the Gulf of Gdansk is presented. Gas bubbles concentration was estimated assuming that nonlinear scattering in soft sediments is similar as in water. Summary, difference and double harmonics generated only by gas bubbles were recorded and used for bubble density estimation. Comparisons of the concentrations received from different nonlinear components show generally agreement in calculated bubble density distributions, although values of densities acquired from almost identical volumes in a single transmission differ.

INTRODUCTION

In many areas of oceanography i.e. in hydroacoustics [1], geology of sea bottom [2] and geochemistry, information about *in situ* bubble concentration is very important because the bubble population in the sea is involved in many processes [5,7].

Gas trapped in the surficial layer of marine sediments may be of biological origin (bacterial reduction of organic matter) or be a product of migration out of deeper layers from hydrocarbons or clathrate deposits [3, 4]. Gas of a biological origin is composed mostly of methane and gas originating from deeper layer may contain methane and other higher hydrocarbons. In the propagation of acoustical waves the role of bubbles occurrence in the water subsurface layer or the sea bottom (especially in the shallow sea) is enormous. The gassy sediments have different acoustical properties comparing to gas-free sediments – e.g. higher attenuation, reflectivity, and lower sound speed. The surface layer of gassy sediments, due to higher reflectivity, could play positive role in the far-range acoustics propagation in the shallow sea.

The knowledge about presence of gases (as methane) in the surface layer of sediments could be used in prediction of "dead" bottom areas, which have an unfavourable effect on the seafloor ecosystems. Conventional methods of gas concentration estimation in sediments involve drilling or coring which are slow and costly. By contrast, acoustic techniques can provide the needed information at a much lower cost with acceptable accuracy and over a large area.

Gas bubbles, mechanically excited at their resonance (with high amplitude oscillation) are strong nonlinear source of acoustical waves. This results in the appearance of various harmonics in signals emitted by an excited bubble [7]. However, in some cases the source of harmonics could be difficult to distinguish because harmonics could be generated in measuring setup and in the bubbly volume. This problem can be partly resolved using different versions of two-frequency echosounding. The advantage of two-frequency method of bubble detection over linear methods is that sum or difference frequencies are generated mostly in the volume of sediment where two beams are crossed. The process of higher harmonics generation by bubbles submersed in the water is theoretically and experimentally well known. However, in the sediments, the problem of estimation of bubble concentration up to now is not resolved as the result of the non-spherical shape of bubbles and complicated acoustical properties of sediments.

In this work, the application of different forms of signals including multifrequency method for detection of bubble population in the sea bottom sediments in the Gulf of Gdansk is presented.

1. THEORY

There is a number of acoustic techniques, differing in complexity, used to measure bubble concentrations *in situ* [8,9]. Among the simplest of these methods are: measurements of linear backscatter by multifrequency echosounders at resonance bubble excitation (e.g. - Nützel, Herwig, 1994), sound speed and attenuation measurements.

Others nonlinear methods used to determine the bubble population, are:

- detection of the second harmonic [11],
- nonlinear mixing of two frequencies at a bubble [10],
- detection of nonlinear response at combination frequency [9], at difference frequency [6] or at sum frequency (by the authors, in the Baltic Sea and in the North Atlantic areas and [13].

Employed here is a variant of nonlinear method used to bubble population estimation based on the echosounder equation determined for each of linear and nonlinear components:

$$\frac{I_{sc}\{\omega,2\omega,\omega_1-\omega_2,\omega_1+\omega_2\}}{I_0}=\frac{\beta\{\omega,2\omega,\omega_1-\omega_2,\omega_1+\omega_2\}\Delta V\{\omega,2\omega,\omega_1-\omega_2,\omega_1+\omega_2\}}{4\pi r^4} \qquad (1)$$

where: I_{sc}- backscattered sound intensity for each linear and nonlinear component,

I_0 - sound intensity of the incident waves,

ΔV -scattering volume, different at linear and nonlinear frequencies, and estimated numerically for different transducer configurations from predicted beam patterns and their crossing,
r - distance from the receiver to the scattering volume,
$\beta\{\omega, 2\omega, \omega_1-\omega_2, \omega_1+\omega_2\}$ - volume backscattering coefficients for different back-scattering processes.

The volume backscattering coefficient for each component is formed as sum of signals radiated by all insonified bubbles:

$$\beta\{...\} = \int \sigma\{...\} n(a) \mathrm{d}a \tag{2}$$

where: $n(a)\mathrm{d}a$ - the bubble concentration in the unit volume (1 m^3), for a range of diameters of $\mathrm{d}a$=1 μm,
$\sigma\{...\}$ - scattering cross section.

The total scattering cross section of the unit volume is approximately equal to the sum of cross sections for each bubble. In our method, we tested the sum, difference and double frequency of pulsating bubble. The scattering cross sections of bubbles embedded in soft water-saturated sediments for different components could be estimated as follows:

$$\sigma_{2\omega_{1,2}} = \frac{36\pi\omega_{1,2}^4\left[(\gamma+1)\omega_\circ^2-\omega_{1,2}^2\right]^2 P_{1,2}^2}{\rho_\circ^2 a_\circ^2\left[\left(\omega_\circ^2-\omega_{1,2}^2\right)^2+\delta^2\omega_{1,2}^4\right]^2\left[\left(\omega_\circ^2-4\omega_{1,2}^2\right)^2+16\delta^2\omega_{1,2}^4\right]}, \tag{3.a}$$

$$\sigma_{\Omega_-} = \frac{\pi\Omega_-^4\left[3(\gamma+1)\omega_\circ^2-\left(\omega_1^2+\omega_2^2-\omega_1\omega_2\right)\right]^2 P_1P_2}{\rho_\circ^2 a_\circ^2\left[\left(\omega_\circ^2-\omega_1^2\right)^2+\delta^2\omega_1^4\right]\left[\left(\omega_\circ^2-\omega_2^2\right)^2+\delta^2\omega_2^4\right]\left[\left(\omega_\circ^2-\Omega_-^2\right)^2+\delta^2\Omega_-^4\right]}, \tag{3.b}$$

$$\sigma_{\Omega_+} = \frac{\pi\Omega_+^4\left[3(\gamma+1)\omega_\circ^2-\left(\omega_1^2+\omega_2^2+\omega_1\omega_2\right)\right]^2 P_1P_2}{\rho_\circ^2 a_\circ^2\left[\left(\omega_\circ^2-\omega_1^2\right)^2+\delta^2\omega_1^4\right]\left[\left(\omega_\circ^2-\omega_2^2\right)^2+\delta^2\omega_2^4\right]\left[\left(\omega_\circ^2-\Omega_+^2\right)^2+\delta^2\Omega_+^4\right]}, \tag{3.c}$$

where $\Omega_+ = \omega_1+\omega_2$, $\Omega_- = \omega_1-\omega_2$, $\gamma = \frac{c_p}{c_v}$.

The volume scattering coefficients for double, sum and difference frequencies are:

$$\beta_{v_{2\omega}} = \frac{\pi\Omega_+^4\left[3(\gamma+1)\omega_\circ^2-\left(\omega_1^2+\omega_2^2+\omega_1\omega_2\right)\right]^2 P_1P_2}{\rho_\circ^2\left[\left(\omega_\circ^2-\Omega_+^2\right)^2+\delta^2\Omega_+^4\right]\omega_1^4\omega_2^4} \times n(a_r) \times \frac{\pi}{4\delta^3 a_r}, \tag{4.a}$$

$$\beta_{v_{\Omega_+}} = \frac{\pi\Omega_+^4\left[3(\gamma+1)\omega_\circ^2-\left(\omega_1^2+\omega_2^2+\omega_1\omega_2\right)\right]^2 P_1P_2}{\rho_\circ^2\left[\left(\omega_\circ^2-\Omega_+^2\right)^2+\delta^2\Omega_+^4\right]\omega_1^4\omega_2^4} \times n(a_r) \times \frac{\pi}{4\delta^3 a_r}, \tag{4.b}$$

$$\beta_{v_{\Omega_-}} = \frac{\pi\Omega_+^4\left[3(\gamma+1)\omega_\circ^2 - \left(\omega_1^2+\omega_2^2+\omega_1\omega_2\right)\right]^2 P_1P_2}{\rho_\circ^2\left[\left(\omega_\circ^2-\Omega_+^2\right)^2+\delta^2\Omega_+^4\right]\omega_1^4\omega_2^4}\times n(a_r)\times\frac{\pi}{4\delta^3 a_r}, \tag{4.c}$$

where: P_1, P_2 – acoustical pressures at a bubble surface, a_r – radius of resonant bubble.
The volume scattering coefficients, reflection and transmission coefficient in the water-bottom interface, calibration parameters and acoustical wave attenuation in sediment used in the equation (1) result in the formula for the bubble density.

The additional attenuation of intensity acoustical waves in sediment was accounted at primary frequencies in the form:

$$\frac{\exp(-2\alpha(\omega)r_B)}{(r_B)^2}, \tag{5.a}$$

where r_B – the path length of the signal in sediments, α-pressure attenuation coefficient at frequency f. Backward propagation loss in sediments at secondary, sum or difference frequency is in similar form:

$$\frac{\exp(-2\alpha_D r_B)}{r_B^2} \tag{5.b}$$

where - $\alpha_D = \alpha\{2\omega,\Omega_+,\Omega_-\}$.

The functional dependence between size and resonance frequency of a bubble embedded in sediments is not so well defined as in liquid. The research of Kargl *et al* [12] indicates that even in the simplest case of the spheroid form a bubble embedded in a saturated sediment has two distinct monopole resonances and are quite different comparing to Minnaert formula. Moreover, there are experimental data indicate [13] that bubble, especially in a few millimetre range of radii, embedded in sediments looks as disks, tubes or wormholes. In this case as in fish swimbladder case several resonances could occur.

2. EXPERIMENTAL SETUP

In series of experiments we have used a set of transducers to sound the surface layer of bottom sediments.

Bubbles were insonified simultaneously at two frequencies, relatively close to each other, near their resonance, with sinusoidal pulses of rectangle envelopes. In the Figure 1 the experimental setup is schematically presented. The system was lowered from the ship board on a crane down to altitude of 10-20 m above the bottom (acoustical beams were looking down). The echosignals were amplified, digitised at 250-533 kSamples/sec with a 16-bit resolution. In the echosignals from gassy sediments, after filtration, two groups of frequencies were analysed – linear - the two primary frequencies (f_1 and f_2), and generated during nonlinear response of medium - the sum ($f_1 + f_2$), doubled ($2f_1$ and $2f_2$) and difference ($|f_1 - f_2|$) frequencies.

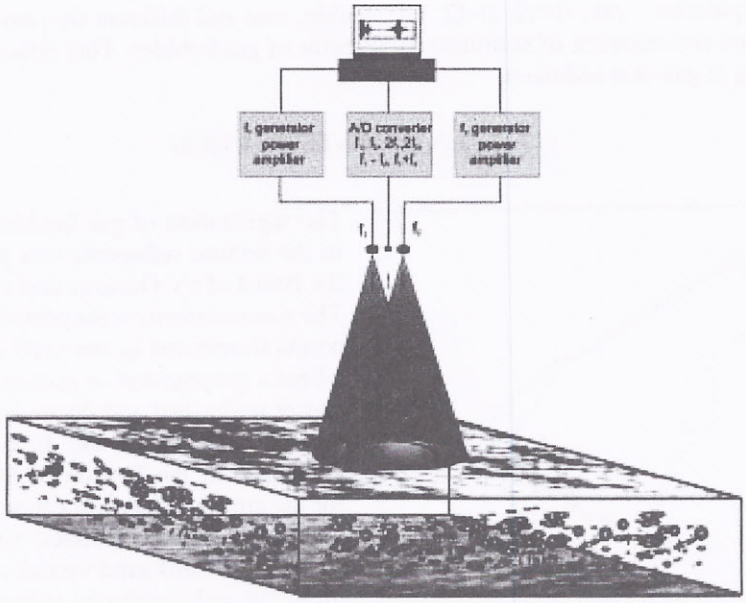

Fig.1 Experimental setup scheme.

For each resolved frequency, signal envelopes are used to parallel estimation of profiles of bubble concentration using the above described algorithm. An example of bubble density estimation is presented in Figure 2.

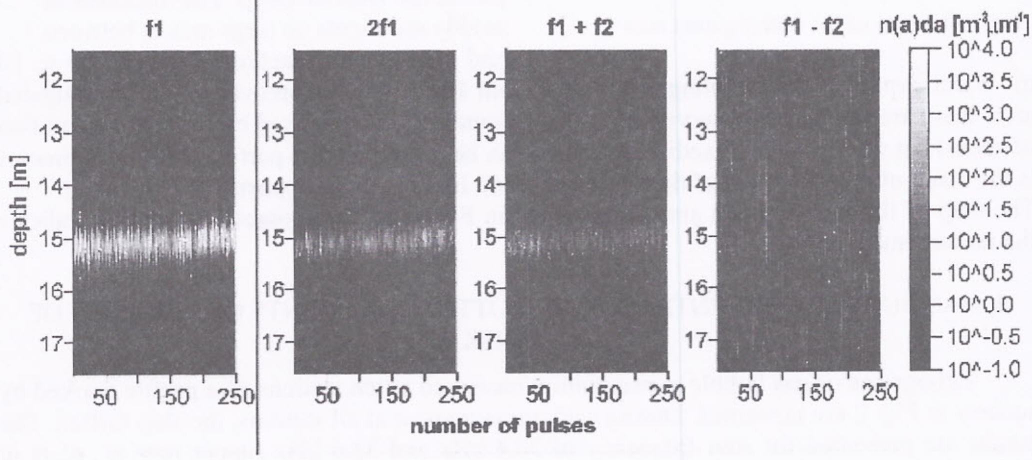

Fig.2 Echogram for frequency f1 and bubble densities estimates from the echo components 2f1, f1+f2, f1-f2; f1=105.5 kHz, f2= 115 kHz. Measurements wer made in the vicinity of the Vistula river estuary (Fig. 3).

The left subplot in Fig. 2 shows the echogram obtained for one of the basic frequency at f1=105.5 kHz. The next three subplots are calculated bubble densities on the basis of registration of frequencies - 2f1, f1+f2, f1-f2. The double, sum and different frequencies in received tion of frequencies - 2f1, f1+f2, f1-f2. The double, sum and different frequencies in received signal are the consequence of nonlinear oscillations of gas bubbles. This effect is not detected in scattering at gas-free sediment.

3. AREA OF INVESTIGATION

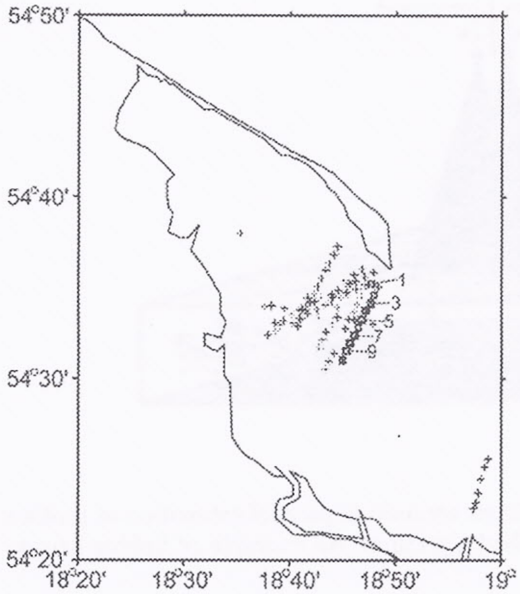

Fig.3 The map of the investigation area

The registration of gas bubbles concentration in the bottom sediments was performed from the board of r/v Oceania and r/v Dr. Lubecki. The measurements were performed at selected points distributed in the Gulf of Gdansk area where a geophysical or geological survey was earlier performed and documented (1:200,000 Geological Map of the Baltic Sea Bottom developed at the Branch of Marine Geology for the area of the Polish economic zone). The investigated area includes variety of sediments from hard sand mixed with gravel and till to silt and semiliquid organic origin fluffy sediments.

Generally, most shallow water areas of the Gdansk Gulf are covered by marine sands of different grain size - from coarse-grained to fine sands. Muddy sediments cover deeper part of the Gdansk Deep. The thickness of muddy sediments on large area is between 3 and 6 m locally reaching thickness up to 10 m. Water depths at the sampling sites range from 10 to 88 m. Moreover, in the investigated area, there are frequently observed acoustical anomalies, characterised by shallow penetration of acoustical waves into soft sediments. So, it can be presumed that part of gases in sediments is the result of migration out of deeper layers from hydrocarbons deposits.

The map of the investigation area is presented in Figure 3. The crosses and squares indicate the measurement points.

4. GAS BUBBLE CONCENTRATION IN BOTTOM SEDIMENTS OF THE GULF OF GDANSK

Echograms of gas bubble concentration measured at ten stations of a profile marked by squares in Fig. 2 are presented. During each measurement at all stations, the ship drifted. The results are presented for sum frequency of 30.4 kHz and 33.6 kHz (upper row of plots in Fig.4) and sum frequency of 105.5 kHz and 115 kHz (bottom row of plots in Fig.4). Numbers placed on the top of consecutive echograms correspond to squares marked in Fig. 2. The distance between the transducers system and the bottom surface is shown on the vertical axes.

The results of measurements illustrate the fact that nonlinearity and in consequence gas bubbles concentration depends on the position of the station in acoustical transect. For stations 1, 2, 7, 8, 9 and 10 (at primary frequencies near 30 kHz) and 1, 2, 3, 8, 9 (at frequencies 105/115 kHz) located at the frontiers of the investigated area, the bubble concentration achieve ~300 $m^{-3}\mu m^{-1}$ (calculated according to the model of nonlinear scattering of bubbles of the setup (stations 3, 4, 6 – 30 kHz; 4, 5, 6, 7, 9 – 115 kHz). The differences between bubble concentrations for 30 and 115 kHz for stations 3, 7 and 10 can be explained by change of locations during the drift of the ship. Measured quantity of concentration is strongly diversified between the stations and does not depend on the distance between transducer and seafloor.

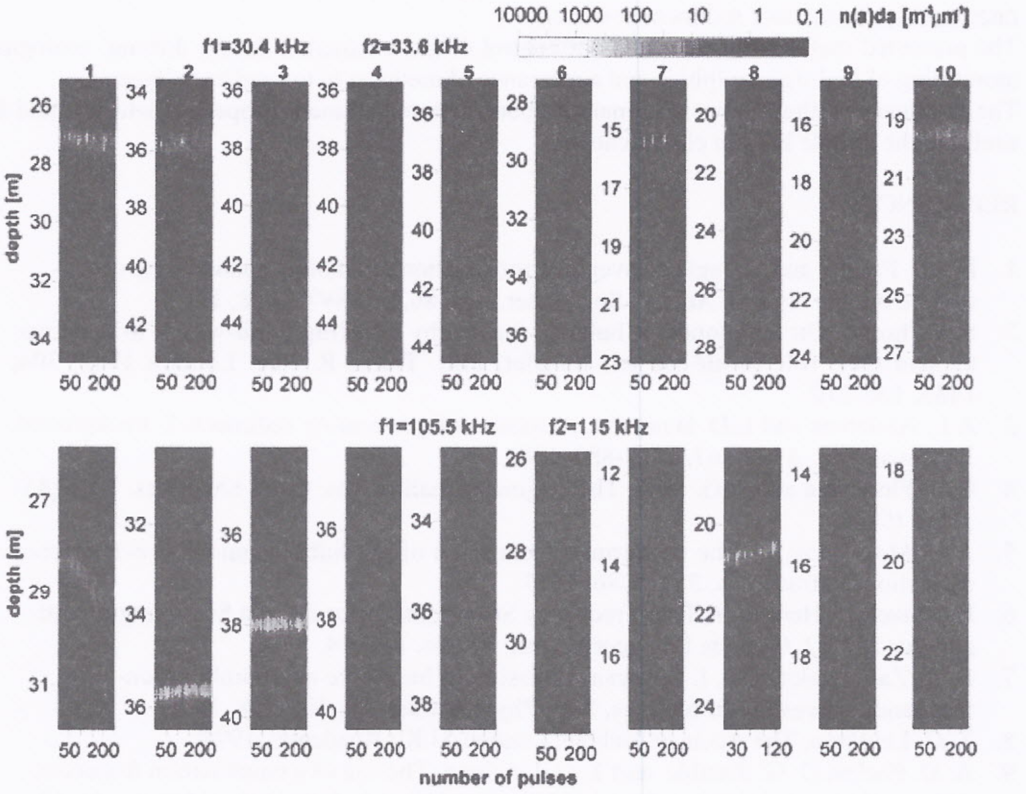

Fig.4 Echograms of gas bubble concentration measured with nonlinear sum method. Top ten plots were made for frequencies of 30.4 and 33.6 kHz, bottom plots were made for frequencies of 105.5 and 115 kHz. Numbers of consecutive echograms correspond to squares marked in Fig. 2.

The biggest values of concentration were registered at stations 1, 2 and 3 (30 kHz) where depths were different. The same situation was observed for higher frequencies where the highest concentrations are recorded for stations number 3 and 8 width different depths. For such diversified bubble concentrations there is the possibility of dependence of resonant frequency from hydrostatic pressure. Together with depth increasing the bubble resonant frequency increasing too. For fixed frequency of emitted signal it causes the change of bubble resonant frequency and increases the bubble radius as the depth increases.

5. CONCLUSIONS

The nonlinear method of gas detection in fluid sediments appears to be potentially sufficient for gassy sediments recognition. Knowledge of the values of generated signals and their transmission rate into the sea floor allowed the concentrations of resonant bubbles in the porous saturated sediments to be estimated. The nonlinear components in echo signals - the sum, difference and double frequencies generated by gas bubbles embedded in sediments - separates bubbles from other sediment scatterers.

The presented method can be useful for control of gas emanation during drilling, ecological monitoring of hydrogen sulphide and appearance of methane in top sediment layers.

The nonlinear methods give information about bottom sediment properties which could be useful in the remote bottom classification.

REFERENCES

1. D. M. Farmer and S.Vagle, Waveguide propagation of ambient sound in the ocean-surface bubble layer, J. Acoust. Soc. Amer., vol. 86, pp.1897–1908, 1989.
2. S.A Thorpe, On the clouds of bubbles formed by breaking wind-waves in deep water and their role in air-sea gas transfer, Phil. Trans. R. Soc. London 1982, 304, 1483, 155-210
3. A.L. Anderson and L.D. Hampton, Acoustics of gas-bearing sediments I. Background, J. Acoust. Soc. Amer., 67, 1865-889, 1980.
4. G.D. Floodgate and A.G. Judd, The origins of shallow gas, Cont. Shelf Res. 12, 1145–1156, 1992.
5. A.O. Maksimov, On the subharmonic emission of gas bubbles under two-frequency excitation, Ultrasonics, 35, 79-86, 1997.
6. B. Nützel, H. Herwig, A Two-Frequency Scatterometer for Bubble Scattering Investigations, IEEE J. Oceanic Engineering, vol. 19, No. 1, 1994.
7. E. A. Zabolotskaya, S. I. Soluyan, Emission of harmonic and combination-frequency waves by air bubbles, Sov. Phys. Acoust. 18, 396-398, 1972.
8. T. G. Leighton, The Acoustic Bubble, London, U.K.: Academic, 1994.
9. A. D. Phelps, D. G. Ramble, and T. G. Leighton, The use of a combination frequency technique to measure the surf zone bubble population, J. Acoust. Soc. Amer., vol. 101, pp. 1981–1989, 1997.
10. C.L. Newhouse and P.M. Shankar, Bubble sizing using the non-linear mixing of two frequencies, J. Acoust. Soc. Amer., vol. 75, pp. 1473–1477, 1984.
11. S. G. Kargl, K.L. Williams and R. Lim, Double monopole resonance of a gas-filled, spherical cavity in a sediment, J. Acoust. Soc. Am., vol. 103, 1998.
12. F. Abegg and A. L. Anderson, The acoustic turbid layer in muddy sediments of Eckernfoerde Bay, Western Baltic: methane concentration, saturation and bubble characteristics". Mar. Geol. 137, 137–147, 1997.
13. Z. Klusek, A. L. Matwiejew, A. I. Potapow and A. M. Sutin, Observation of non-linear scattering of acoustical waves at sea sediments, Acoustics Letter 18, No 11, 198-203, 1995.

This paper was made with support from State Committee for Scientific Research of Poland (research project no. 8 T12B 006 20).