THE ACOUSTIC EVIDENCE FOR GAS BUBBLES IN THE LAKE KINNERET SEDIMENTS

JAROSŁAW TĘGOWSKI[1], ILIA OSTROVSKY[2], MATEUSZ ZAMARYKA[1]

[1]Institute of Oceanography, University of Gdansk,
al. Marszalka Pilsudskiego 46, 81-378 Gdynia, Poland
j.tegowski@ug.edu.pl
[2]Israel Oceanographic & Limnological Research, Yigal Allon Kinneret Limnological Laboratory, P.O. Box 447, Migdal 14950, Israel

The changes in gas content of bottom sediments are associated with rapid alterations of the ambient conditions (climate change, eutrophication, water level fluctuation, etc). In this paper we present results of acoustical measurements of sound scattering at gassy sediments in the subtropical Lake Kinneret (Sea of Galilee), where the 120 kHz single beam echosounder for bottom recognition was used. Measurements were carried out over a 10-year period along 14 standard transects. The echo parameterization method was applied to study acoustical features of bottom deposits and their variability in relation to sedimentary content of gas bubbles. Particularly, we examined the influence of water level fluctuations, affecting the presence of gas bubbles in the surface sediments on sound scattering and echo envelope parameters (spectral, wavelet, fractal, statistical and energetic). Presented results indicate the usefulness of the proposed method of backscattered signals processing for monitoring of the seafloor features.

INTRODUCTION

The gas in sediments has been detected in marine and freshwater aquatic systems. The main biogeochemical source of gas in sediments (methane and carbon dioxide) is *in situ* bacterial decomposition of organic matter. Other sources of sedimentary gases are hydrates, submarine geothermal processes, and infiltration into sediment of gases dissolved in the waterbody due to turbulent processes [1]. Climate change, eutrophication, global increase in temperature as well as water level fluctuations have an important role in the formation of gas bubbles in the top layer of bottom deposits. Presence of gas in sediments causes the changes of their elastic properties manifested in changes of acoustic wave velocity, sound attenuation and reflective features of the upper sediment layer [2, 3].

Subtropical Lake Kinneret located in the north part of Israel is a good example of fresh water reservoir, where biogeochemical processes are responsible for high gas saturation in the sediments and the observed gas outflows from the bottom at low water level [4, 5]. The water surface of the lake is at -209 m above sea level (masl) when lake is completely full. The maximum length of the lake is 21 km, its width is 13 km, and its maximum depth is 43 m (Fig.1.). The bottom sediments in shallow areas are sandy, while the central area it is muddy [6]. The water level is characterized by large fluctuations. On a multi-annual basis, the water level can declines down to 6.5 m below its maximum level, while the mean annual water level fluctuations are usually within 1.5-2 m. Such large fluctuations in water level cause changes

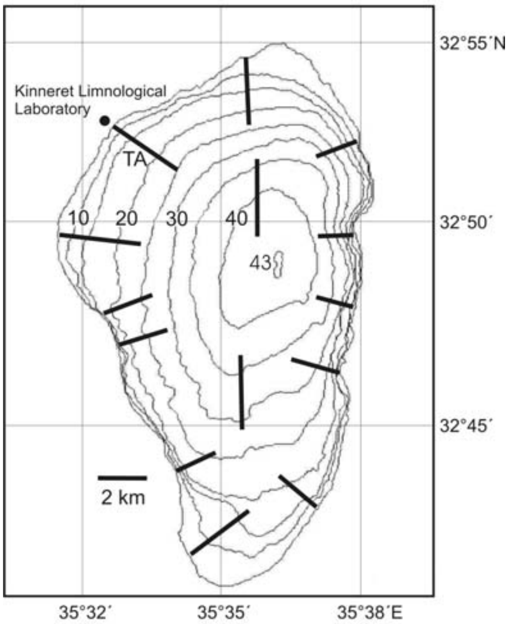

Fig.1. Bathymetric map of Lake Kinneret showing the position of acoustic transects

in bottom sediments. The acoustical, biological and geochemical measurements of surface sediments were studies by Dr. Ilia Ostrovsky [4-11] and allowed examination of a set of different echo envelope parameters to characterize the features of bottom sediments in Lake Kinneret in relation to water level fluctuation.

1. MEASUREMENT METHODOLOGY

Acoustic sampling of the Lake Kinneret bottom carried out with a single beam BioSonics DE5000 echo sounder operating at 120 kHz. The data were collected along 14 standard transects depicted as segments in the bathymetric map of the lake (Fig. 1). Twelve transects were placed perpendicular to the lake shoreline, while two were situated in the central northern and southern areas. All transects were located in the areas containing all types of soft bottom sediments. Acoustic measurements along the same transects were repeated over a 10-year period. The basic measurement parameters were: beamwidth - 6.5°, ping rate - 5 s^{-1} and pulse duration – 0.2 ms. The transducer was mounted on a towed fin for stabilisation.

Example of 120-kHz echogram of gas outflow from the gas-saturated deposits is shown in Fig. 2. The vertical cloud of scatterers below 15-20-m depth could be attributed to sedimentary “dust” that might be from the lake floor by the gas seepage. Tracks of rising

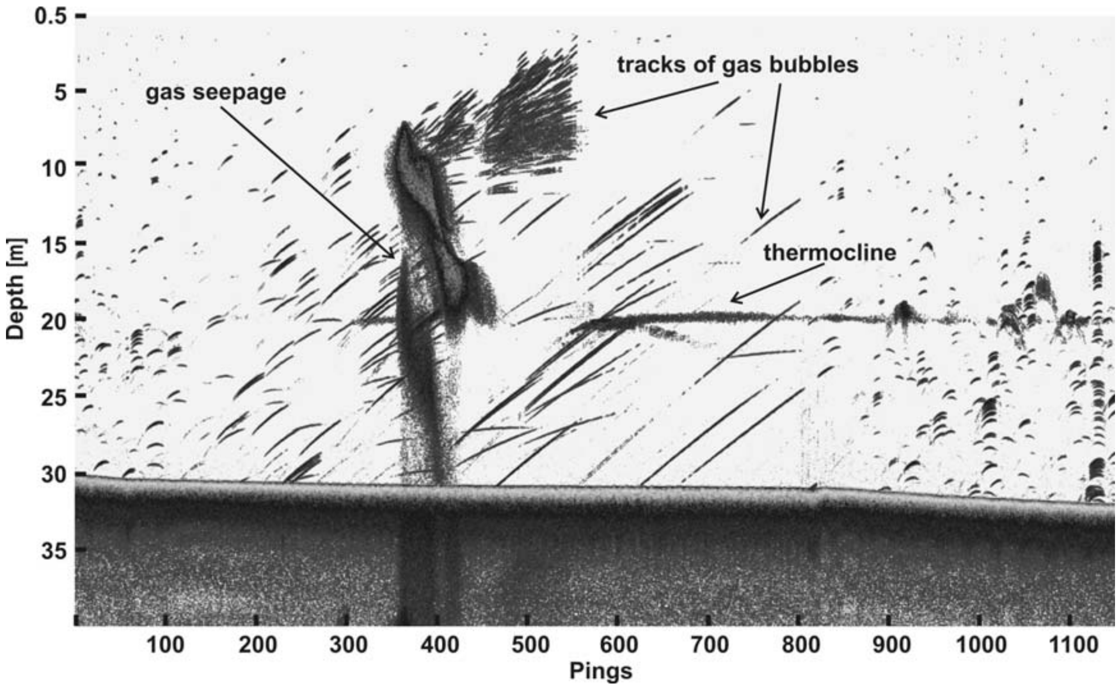

Fig.2. Example of gas seepage and tracks of flowing up gas bubbles in the water body in the Lake Kinneret

bubbles are clearly seen as inclined lines. The long horizontal noisy trail in the middle part of the echogram (at ~20-m depth) is the thermocline containing various scatterers (suspended particles, plankton, gas bubbles). The analyses of bubbles trapped promptly after their emission showed that methane was the dominant gas component [4, 5, and 6].

Additional observations involved stationary ground truth sampling were performed with Ekman-Birge grab at several stations located along a northwestern offshore transect, where all types of soft sediments are present [6, 11].

2. PARAMETRIC ANALYSIS OF SINGLE BEAM ECHOSOUNDER DATA

Signal correction procedures were applied before the parameterisation of echo envelopes. For each set of 20 consecutive pulses only echoes of energy greater than 75% of maximum pulse energy (in the set of 20) were taken into account. Such procedure assured that vertically propagated pulses were taken for further analysis. The next procedure compensated dependency of echo shape on the bottom depth. Following Caughey and Kirlin [12], we applied algorithm of resampling of the signal propagation time t as follows:

$$t' = t\frac{H_0}{R}, \tag{1}$$

where t' is rescaled time, H_0 – reference depth, R – distance from transducer to the bottom.
The reference depth H_0 was established for 10m and TVG function for $30\log_{10}R$ [16] as compensation of echo intensity loss due to depth increase.

For each of such prepared echo signals the set of 64 diversified echo envelope parameters was calculated [13, 14, 15, and 11]. Echo features in the first group, describe the energy or parts of energy coming from the surface scattering - E_{surf} and volume scattering (echo tail) - E_{vol}. The next important parameters were statistical moments of an envelope and autocorrelation length. Very sensitive for signal fluctuations are spectral parameters and especially spectral moments – m_r (r = 0-7) and theirs combinations - spectral widths ε^2, ν^2 and skewness γ:

$$m_r = \int_0^\infty \omega^r S(\omega) d\omega\,, \tag{2}$$

$$\nu^2 = \frac{m_0 m_2}{m_1^2} - 1\,, \qquad \gamma = \frac{\tilde{m}_3}{\tilde{m}_2^{3/2}}\,, \tag{3}$$

where $S(\omega)$ is power spectral density of echo envelope. From the slope β of spectrum, the fractal dimension was estimated ($D = (5-\beta)/2$) [17].

Other group of echo envelope features consists of wavelet transformation parameters calculated for Coiflet, Daubechies and Meyer wavelets. There are wavelet energies E_{wav} computed for dyadic scales $a=2^j$ (where j=1-7) as the sum of transformation coefficients for chosen scale a. On the basis of wavelet transform, the Hausdorff exponent H and fractal dimension $D_{wav} = 2-H$ was calculated (for different wavelets) [13]. Moreover, the combinations of the mentioned above parameters were tested in order to find new variables that have higher sensitivity to sediment features and their variations in response to fluctuation of environmental conditions.

3. RESULTS AND DISCUSSION

Sediments distribution along offshore transects show similar pattern in different locations. Sandy bottom is characteristic for shallow areas; the proportion of silt and clay gradually increases toward the deeper part of the lake. Such a pattern of sediment distribution is reflected in some features of backscattered signals.

Fig.3 presents the variability of chosen echo envelope parameters computed for backscattered signals. The first analysed feature is a ratio of energy scattered from the bottom surface to energy scattered by sediment volume E_{surf}/E_{vol}, (Fig. 3b). In the shallow sandy bottom area (at the beginning of transect), the most of energy is scattered from the lake floor surface (the ratio of energies is ~10). In the deeper part, the volume scattering takes the advantage over surface scattering, due to the deeper penetration of sound in acoustically soft muddy sediments. The observed dependence has changed in the deepest part of transect, where, once again, the surface scattering prevails the volume scattering. Although, in this area soft muddy sediments predominate and thus acoustic signal should penetrate deeper, the observed backscattered signal shows opposite tendency. The later can be explained by the presence of gas bubbles in the upper layer of sediments. The bubbles are strong scatterers and form an acoustic screen for the incident signals in the surface layer [17].

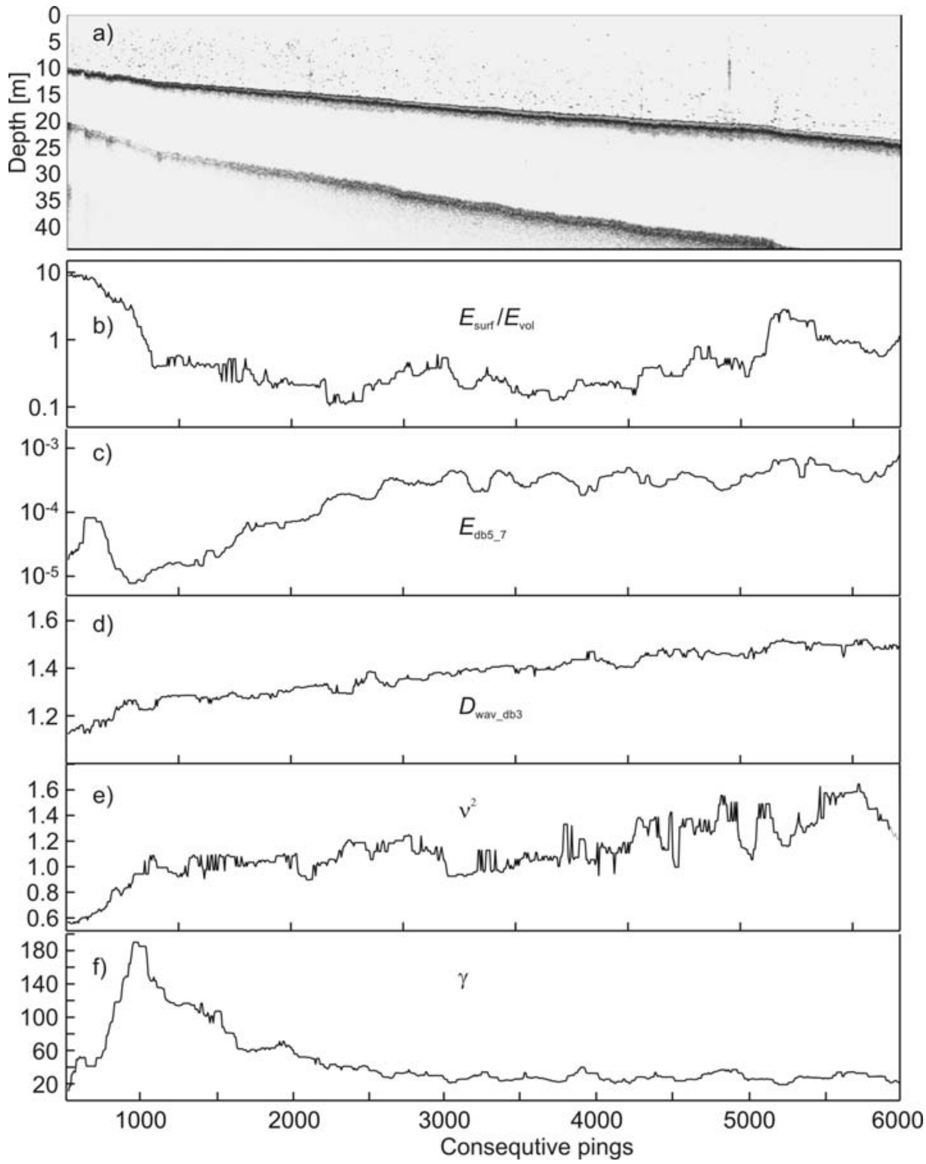

Fig.3. (a) Echogram of the offshore TA transect collected on October 30, 2002. Echo envelope variables: (b) ratio of surface scattering energy to volume scattering energy E_{surf}/E_{vol} , (c) E_{db5_7} - energy of Daubechies wavelet of order 5 and scale a=2^7 , (d) D_{wav_db3} – fractal dimension computed using Daubechies wavelets of the third order, (e) spectral width – ν^2, (f) spectral skewness – γ. TA transect is positioned between Kinneret Limnological Laboratory and lake interior (Fig. 1)

The other features of scattered signals are visible in the next successive plots of Fig. 3. The spatial distribution of three echo envelope parameters - E_{db5_7} - energy of Daubechies wavelet of order 5 and scale a=2^7 (Fig. 3c), D_{wav_db3} – fractal dimension computed using Daubechies wavelets of the third order (Fig. 3d) and spectral width – ν^2 (Fig. 3e), generally increase with bottom depth. They are wavelet, fractal and spectral features sensitive to level of surface corrugation and shape of sediment layered structure, and reflect complexity of geomorphology of the lake floor. The spectral skewness, γ (Fig. 3f), describes the shape of the echo envelope spectrum. This variable rapidly increases between the shallowest locations and a certain bottom depth. This can be associated with an increase in echo length with bottom depth due to greater proportion of mud and small fluctuations in echo signal. Then, below a certain depth threshold, the spectral skewness decreases monotonically. The later can be related with the fact that echo from gassy sediments is smoother and its spectrum is more symmetrical and has shorter shape than the echo signal from the gas-free sediments.

The Fig 4 shows the changes in some echo envelope parameters with depth at different water levels. The left figures (4a, 4c, and 4e) portray situation on December, 30, 2002, when water level was -214.32 masl, while right figures (4b, 4d, and 4f) portray situation on May, 21, 2003, after rapid raise of the water level to -209.72 masl.

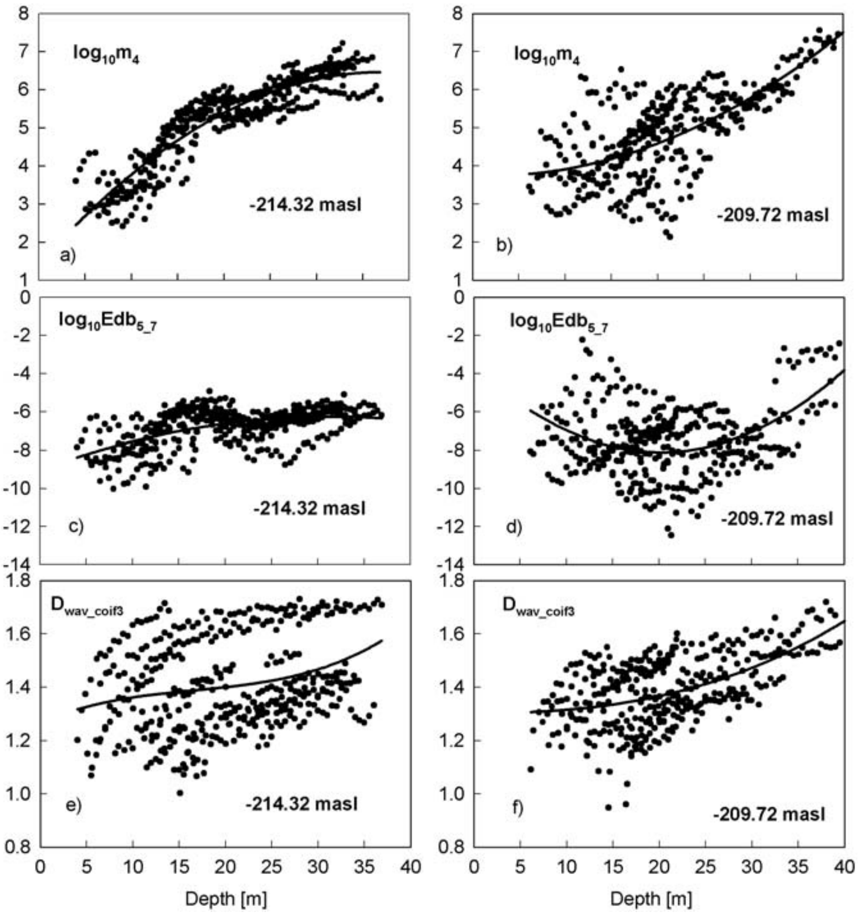

Fig.4. The depth dependences of selected echo parameters along 13 offshore transects (left figures – December, 30, 2002) and 12 transects (right figures – May,21, 2003). The data were binned using a 0.5-m depth interval, and each point represents the mean of usually 10–100 measurements

The volume of gas bubbles in the sediment depends on hydrostatic pressure at the bottom, i.e. it can be associated with water level in the lake, such that large bubbles can be abundant in sediments at low water level, while at the high water level bubbles are squashed and some of them may vanish. Manifestation of this rule is clearly observed for m_4 (fourth spectral moment) and E_{db5_7} (energy of Daubechies wavelet of order 5 and scale a = 2^7) (cf.

Figs.4a, 4b, 4c, and 4d). In case of low water level, the presence of gas bubbles in deeper muddy sediments causes the backscattered signals to be shorter and more smooth than the backscattered signals scattered at the bottom sediments that contain small amount of gas bubbles (Fig. 4a, 4c). The small dispersion of the both parameters at the low water level supports the findings mentioned above. The opposite situation was characteristics at the high water level (Fig. 4b, 4d), where signals scattered from the lake floor have long and corrugated tails, as a result of volume scattering. This is a reason of large dispersion of both parameters.

Dissimilar response to water level change shows $D_{\mathrm{wav\_coif3}}$ (fractal dimension computed using Coiflet wavelets of the third order) (Fig. 4e, 4f). The presence of gas in sediments causes large diversity of backscattered signal shapes and respective large dispersion of $D_{\mathrm{wav\_coif3}}$. For small abundance of gas bubbles in sediments (i.e. at high water level) the dispersion of this variable is also smaller.

4. CONCLUSIONS

The data presented here indicate strong relationship between features of echo signals and physico-chemical properties of soft bottom sediments. The content of gas bubbles in sediments is one of the key factors affecting their acoustic features. These results also show an importance of long-term acoustic monitoring of bottom sediments for better understanding the changes in lake floor properties in response to variation of ambient conditions (e.g. water level fluctuation, climate change) and for studying the relationships between acoustical and sedimentological variables.

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