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ON THE CONCENTRATIONS OF GAS BUBBLES MEASURED ACOUSTICALLY IN THE BALTIC SEA - WIND AND TIME DEPENDENCES.

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ABSTRACT

A linear and nonlinear two-frequency acoustical technique has been used to make in situ measurements of gas bubbles profiles in the Baltic Sea. At three pairs of frequencies namely 30/35, 57/63 and 110/115 kHz spectral components of linear and nonlinear backscattered signal were extracted and their wind and depth dependences have been calculated. Preliminary results of nonlinear backscattering from the subsurface layer of gas bubbles in different hydrological conditions are presented.

INTRODUCTION

Wind velocity, temperature and salinity constitute the decisive factors for gas bubbles concentrations and their size spectrum in seawater. However, other mechanisms, some of which still unrecognised, could be involved in processes of gas bubble emission.

The salinity and chemical composition of marine water profoundly change the process of microbubble formation. As much as order of magnitude, the increase of the bubble concentration was observed in laboratory for salt water vs. fresh water over the entire radii range [1], [2]. This fact should be accounted when we try to extrapolate oceanic results to the less saline (2 - 8 ‰) Baltic water environment.

The other problem which arises during the acoustical bubble counting in the Baltic Sea are errors induced by abundant scattering layers of nekton beneath the sea surface at night hours and especially during the blossom period.

As part of our current effort in understanding the interactions between the physics and biology in the Baltic sea we examined the diel migrations and gas bubble production. The initial purpose of the investigations was to measure gas bubble concentration and their around day changes correlated with biological productivity in this area.

The other goal of our measurements was to find the reason of tremendously big differences between bubble concentration data obtained by many researchers, that is, a few orders at the same wind velocity, although conducted in different areas and with different methods.

THEORETICAL BACKGROUND CONSIDERATIONS

The alternative to the most common resonance methods practised in the bubble counting could be the determination of bubble number using their nonlinear backscattering response. The latter technique apart from the higher selectivity of bubble radii and lower unambiguity gives the opportunity to detect gas bubbles inside the swarms of marine organisms as well as in sediments. The advantage derives also from the fact that nonlinearity of gas bubbles is of the order of thousands times higher than nonlinearity of other inhomogeneities in the sea. In our investigations the bubbles were insonified at two frequencies, resonably close to each other, so that a bubble was driven at the resonance frequency. Because of nonlinear behaviour of the bubble driven to high amplitudes, the fraction of incident energy will be converted into harmonics and secondary (difference and sum frequency) spectral components like $2f_1, 2f_2, f_1+f_2, |f_1-f_2|, \ldots$. Among those spectral components the sum frequency f_1+f_2 which could be generated only in the bubble medium was used to detect and calculate density of the gas bubbles in the subsurface layer.

The objective of the investigations was to compare the echolevel of noncoherent echo from undersurface inhomogeneities at primary versus harmonics and sum frequencies.

When bubbles are randomly distributed in space, and their concentration is not too high, a noncoherent backscattering process prevails and contribution from every bubble add quadratically. In this case a nonlinear volume backscattering coefficient β could be defined in similar way as in linear acoustics when [3]-

$$\frac{I_{sc}}{I_0} = \frac{\beta_\omega \Delta V}{4\pi R^2} \qquad (1)$$

where - I_{sc} - backscattered intensity,
I_0 - intensity in the incident wave,
ΔV - scattering volume,
R - distance from the transmitter to the scattering volume.

The value of β_ω is the sum of all the bubble cross sections and could be calculated using formula $\beta = \int \sigma n(a)\, da$

where n(a)da - the bubbles concentration in the unit volume (1 m^3), for a range of diameters of [a,a+da] (da=1 μm). If the form of functional dependence $\sigma=\sigma(a)$ is taken into account, we could assume that β depends only on the bubble concentration $n(a_\omega)$ with radius a_ω around resonance frequency (in the layer beneath the sea surface in SI units we have $a_\omega f$=3.26).

In case of linear backscattering, using the resonance approximation, the linear backscattering coefficient is given by [4] :

$$\beta_\omega = \frac{\pi}{2} n(a_\omega) a_\omega^3 / \delta; \qquad (2)$$

$\delta \cong 0.1$ in frequency range of 5-200 kHz.

The nonlinear acoustical intensity at sum frequency from scattering volume dV could be given in the form -

$$I_{NLN} = \frac{\left(p_{01}{}^2 + p_{02}{}^2\right)}{R^4} \beta_\varpi e^{\left(-2\alpha_\omega R\right)} e^{-2\alpha_\varpi R}\, dV \qquad (3)$$

where - p_{01}, p_{02} - pressure at 1 m distance from transmitters,

$$\varpi = \frac{\omega_1 + \omega_2}{2}$$

$\alpha_\omega\ \alpha_\varpi$ - attenuation coefficients in [Nep/m] for primary and secondary frequencies,

dV -denotes the scattering volume at nonlinear frequencies, it is defined as the volume of an intersection of the two primary frequency beams (here calculated numerically).

For harmonics and the sum frequency, β was proposed in an approximate way as analytical expression [4,7]:

$$\beta_\varpi \cong \beta_{2\omega} = \frac{\pi^2 \gamma^2 n(a_\omega) P_0^2}{\rho_0^2 \omega^4 a_\omega \delta^3}; \qquad (4)$$

a_ω - bubble radius at the resonance frequency
ρ - medium density,
δ - damping constant,
γ - ratio of specific heats of bubble gas,
ρ_0 - density of surrounding water.

Above formula, together with the equations (1), (2) and (3), give a theoretical basis for bubble density calculation.

EXPERIMENTAL INVESTIGATIONS

<u>Area of investigations and environmental considerations</u>

The measurements were performed during the Baltic expeditions of research vessels „Oceania" and "Kopernik" in summer time of 7-13 May 1995, 17-20 April and 18-22 August 1996. The investigations were taken at three locations in the Southern Baltic Sea area

(Gdansk Gulf). Measurements were run from 56 hours to 96 hours and the data were recorded each hour.

The wind velocity measured at the height of 4 m above the sea surface and converted to the standard height of 10 m was within range of 0 to 12 m/s.

The temperature of surficial water at the stations differed inconsiderably in the range from 11 to 18 °C with the salinity around 7 ‰. Exceptional weather and salinity conditions occurred in April 1996. During 56 hours of the measurements the still weather prevailed with the wind speed measured at the height of 4 m not exceeded 4.6 m/s (mean value of 2.8 m/s) and the surficial water composed of fresh water layer of the Wisla River origin. No biological catches were made during the acoustical recordings and correlations could be performed only with the physical parameters such as wind velocity, tempe-rature or salinity.

Experimental set-up

The measurements were conducted using the set of four piston sandwich type transmitters working synchronously in pairs at two frequencies. As a receiver a piston transducer was used, the one for all frequencies. All transducers were mounted to a steel frame and arranged in a upward near-vertical position. The resonance frequency of the transmitters were near 30/35, 57/63 respectively and differed slightly in different experiments. The frequency around 110/120 kHz was generated from 60 kHz transmitters. The adjacent frequency transducer separation was from 0.5 m to 0.8 m. The beamwidths of the transmitters varied from 15/16° at 30 kHz to less than 7° at 110 kHz. The transmitters and the receiver were suspended at the average depth of 10.5 -12 m. Field calibrations of the transmitters source level and the receiver sensitivity were carried out using Bruel-Kjaer 8104 hydrophone. As a source two channel power amplifier of ultrasounds was used with output power in each channel of order of 0.5 kW. Pressure amplitudes as referred to the distance of 1 m were equal 55 and 57 kPa at 30 kHz, whereas 77 and 100 kPa at 60 kHz. The system was not calibrated at 110 kHz. The level of primary waves was sufficiently for generating nonlinear processes in bubble population. The amplitude of the second nonlinear component at amplifier output was order of 1% comparing to the basic frequency. The sequences of full echosignal were digitalized at a rate - in case of primary frequencies at 30 kHz - 250 Ksamples per second, for higher primary frequencies 307/363 and 500 Ksamples per second respectively. The acoustic echosignal was corrected for spreading and attenuation losses. The time sequence of scattering volume for each transducer was calculated numerically. The data acquisition system chosen for this project was based on the DATEL SRC414b2 (USA) ADC with theoretical dynamic range about 80 dB (14 bits). All digitized data were stored on hard disk for analysis. On each station six series of echosignals were registered (three pairs of primary frequencies, two times for each pair - one for noncoherent and the other for reflected from sea surface component). Spectrum calculations, digital filtering and echoprofile estimation of each of interest spectral components were performed. After detection of the surface sea echo, the received time series were shifted in such a way that the surface samples appeared at the same place for each echo signal. To avoid process of generation of the sum frequency inside a voltage preamplifier the maximum attention was given to the gain of the signal amplifier.

RESULTS AND DISCUSSIONS.

Wind dependences.

For the wind velocity above the white-caps threshold level (6-7 m/s) the density of surface bubbles can be described according to the frequently cited form [5]:

$$N(a, z) \propto a^{-n} U^{m} \exp(-z / L) \qquad (5)$$

where - $U=U_{10}$ - wind velocity at the high of 10 m,

for depths range of $z \leq 3$ m, $3.5<n<5$, $m \approx 4.5$, a- bubble radius and L - bubble entertainment depth.

In our investigations the values of m coefficient obtained for the May 1995 series were relatively low and are equal: at 30 kHz m=1.4 , and at 60 kHz m=1.8.

Depth dependence

The depth dependence of bubble densities is usually postulated in exponential form. For wind speed in the range of 8-13 m/s the normalised number of gas bubbles could be approximated by formula [6]

$$\frac{N(z)}{N_0} = \exp(-z / L) \qquad (6)$$

We should differenciate our data into two groups dependent on the mechanism producing the gas bubbles. In the first group we have data with the exponential function of the vertical dependence of the bubble concentration (the May and August data). This is the case when the bubbles were produced mostly by breaking waves. In the second set of data the almost constant with the depth layer of bubbles existed frequently and at night the increase with the depth the gas bubble concentration could be observed (April, 1996). The last occurrence is due to free and inside bodies biological bubbles rather than physical factors.

We have found that for wind speed less than the threshold wind velocity v<6.5 m/s the values of L are almost constant. Beyond this wind velocity the linear growth of the bubble entraintment depth was observed. For the data received with the nonlinear method our estimation of the L values are given in Figs. 1 and 2. Two straight lines were fitted to the data in two regions - under and above the wind velocity of 6.5 m/s.

Estimation of the L gives :
at 30 kHz, for wind velocity v<6.5 m/s <L>=1.22,
at 60 kHz, for wind velocity v<6.5 m/s <L>=1.21.

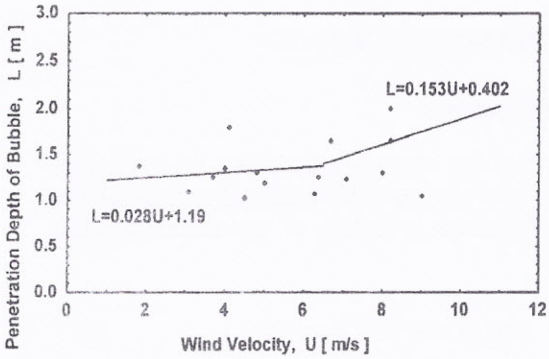

Fig. 1 The wind velocity dependence of the entertainment depth of bubbles with radius $a_0 \approx 50$ μm recorded in May 1995.

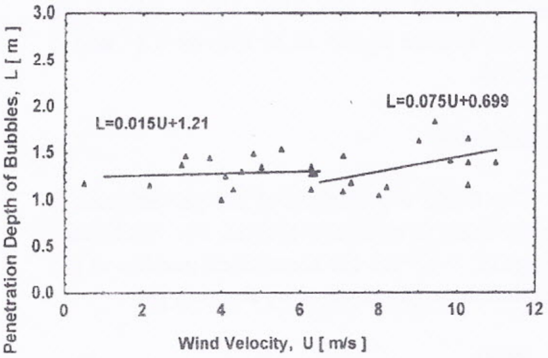

Fig. 2 The wind velocity dependence of the entertainment depth of bubbles with radius $a_0 \approx 100$ μm

Diurnal effects:

As Medwin observed [3], in absence of white-caps at the sea surface the density of gas bubbles increased at sundown what correlated with the toward surface migrations of sound scattering layers. In our measurements the most evident example of the influence of biological factors on bubble presence was recorded in April 1996. During the night's hours more bubbles were observed in the deeper layer than near the sea surface (Fig. 3a) 3b)). We suppose that the gradient of salinity in the upper 2 m thickness layer formed a barrier and at the same time attracted nekton which ussually migrate to the surface. What was more unexpected the gas bubbles concentration at 60 kHz was significantly lower.

Figures 3a) and 3b) show bubble densities measured under calm conditions in the layer from 0.5 to 6 m using nonlinear methods at primary frequencies 31.5/34.6 and 57.3/62.5 kHz. The numbers of bubbles were transformed to log values because of their high dynamics so the results are presented in the form of either the volume backscattering strength or logarithm of bubble densities at primary frequencies, where n is the number of bubbles per unit volume (in m^3) per unit radius increment (in μm). The most striking result obtained from this experiment was lower density of bubbles with lesser radius.

Others periodicities.

Using the Maximum Entropy Method for the data collected in May 1995 spectral dependences has been calculated. In nonlinear case in spectra of bubble density for the depths range from 0.5 to 3 m a number of local maxima were observed:

for frequencies of 30 and 35 kHz (bubble radius $a_0 \approx 100$ μm) -peaks with periods of 15 h, 4 h 30 min and two small maxima near 2.66 h,

for 57 and 63 kHz ($a_0 \approx 50$ μm) - 23.5 h, 5.25 h and a weak peak at 3 h,

for 100 and 110 kHz ($a_0 \approx 25$ μm) - 20 h , 4.2 h and 3.3 h.

The very interesting feature of the observed spectra is that the same frequencies could be found among hydrodynamical phenomena existing in the investigated basin - inertial currents with period of 14.3 h and seiches of Gdansk Gulf with periods of about 4 and 5 hours. We suppose that changes of pressure could induce bubble emission from the thermocline and the sea bottom. The presence of the shortest periods is believed to be caused by internal waves in the area.

The spectra of bubble density obtained on the basis of linear backscattering technique have some distinctictive differences if compared with the other method - for example at 30 kHz two peaks alone were observed with 24 and 2.5 hour period.

The form of latter spectra could be explained as reflection of the biological activity (migrations) in the area.

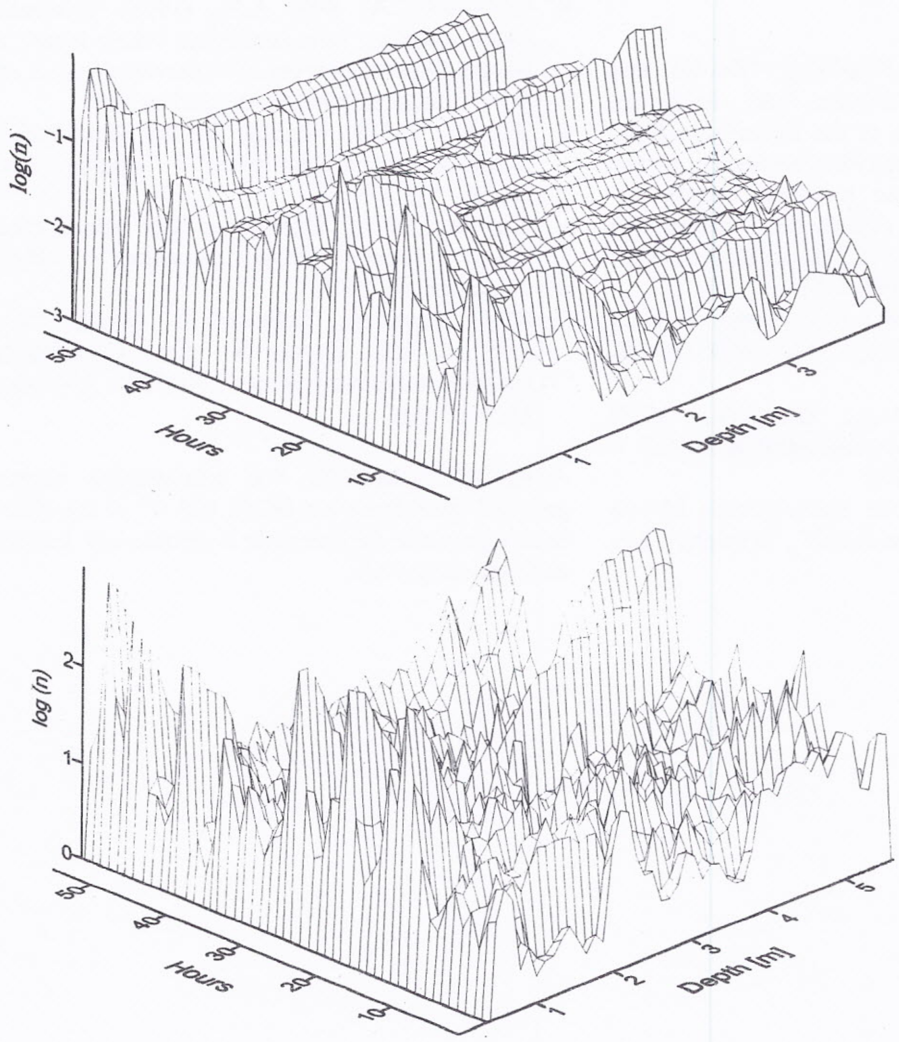

Fig. 3 a), b) Evolution in time of observed bubble concentrations in April 1996, n is the number of bubbles per unit volume (in m^3) per unit radius increment (in μm)- $[m.^{-3}\mu m.^{-1}]$. The results were obtained at the summary frequency. Data are presented for pairs of frequencies of 57.3 and 62.5 kHz in the upper figure and 30.5 and 34.6 kHz in the lower part. The measurements started on 17th April at 2000 h local summer time.

CONCLUSIONS

The presented results are important for interpreting the impact of targets of biological origin on estimation of gas bubble density, especially under calm weather condition. Both linear and nonlinear techniques are capable of providing similar results if biological factors are not present at the sea.

The authors have arrived at the conclusion that in this case good quality agreement between two methods was reached. Otherwise the comparison of the bubble densities derived form linear and nonlinear methods shows the considerable difference in bubble numbers at the same profiles. Some differences may be explained due to different techniques (linear and nonlinear methods) but the difference is noticeably and well above the experimental errors.

The differences between these techniques probable were being most influenced by the presence of small nekton at night. Analysing the periodicity of gas bubble concentration we has concluded that the bubbles population must be supplemented by other than the sea surface sources distributed in water column possibly at the thermocline, and at the sea bottom.

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