Acoustic detection of gas bubbles in the sea

OCEANOLOGIA, 28, 1989
PL ISSN 0078-3234

Hydroacoustics
Backscattering
Gas bubbles
Baltic Sea

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Manuscript received March 2, 1989, in final form July 25, 1989.

Abstract

Acoustic determination of the concentration of gas bubbles in the sea is based on the phenomenon of resonant backscattering. A bubble of a definite size resonates with an incident acoustic wave of a precisely defined frequency, inversely proportional to a bubble radius. On a basis of the determination of the backscattering intensity of various sound frequencies, the number of bubbles of various dimensions can be determined. The values measured *in situ* allowed an approximation of the dependence of the number of bubbles on their size and the depth, as well as an evaluation of the effect of bubbles on the sound propagation conditions in the Baltic.

1. Introduction

Gas bubbles floating in the sea depth play a crucial role in a number of physical, biological, and chemical processes. They determine the gas exchange between the sea and the atmosphere. Produced mainly by breaking wind waves forced into the sea by turbulent mixing, they participate in the transport of biological and chemical substances, as well as in the formation of aerosols as a results of breaking at the surface. Intensity of these processes depends directly on the concentration of microbubbles. On the other hand, bubble clouds constitute a barrier for ultrasonic waves propagating in water, causing their scattering and attenuation, and changing the propagation rate. The presence of bubbles reduces the "transparency" of a medium and must be taken into account during interpretation of any hydroacoustic data.

As a result, measuring methods enabling the determination of gas bubbles concentration in water are searched for. Scarce *in situ* experiments (Medwin, 1970, 1977; Johnson, Cooke, 1979; Kolobayev, 1975; Akulichev *et al*, 1986; Lovik, 1980) were carried out either by optical, or by acoustic methods, and concerned the ocean regions. Due to diversity of methods and experimental conditions (sea region, state of sea, thermal conditions), the obtained results are characterized by very diversified absolute values, yet they always demonstrate a decrease of the number of bubbles with an increase in depth and bubble size. In spite of these clear tendencies, it seems unfeasible to derive a universal formula describing the dependence of the concentration of bubbles in the sea on all the parameters, therefore a method applicable in a given region and under particular conditions should be developed. Determination of the coefficient of backscattering of sound in the sea depth can constitute such a method owing to specific acoustic resonant characteristics of bubbles.

2. Backscattering of sound by bubbles—sonar equation

Let us consider the dependence between backscattering of acoustic energy and the number of scattering resonant bubbles. Geometry of the experiment is as follows (Fig. 1): a transmitter (wave source) and a receiver (hydrophone) are situated in the centre of a spherical co-ordinate system. At the moment $t = 0$ the transmitter emits rectangular acoustic pulses lasting for the time τ with a sine modulation of the frequency f. At a given moment t, the scattered signal is recorded in the volume V_{rev} removed by $r = ct/2$ from the source, where c is the speed of sound. The thickness of this spherical layer is equal to $c\tau/2$. If we assume that the energy emitted in unit time into unit solid angle at the direction (θ, φ) is equal to $F(\theta, \varphi)$, then the intensity of the reverberation signal at the time t is described by the following dependence (Clay, Medwin, 1977; Szczucka, 1986):

$$I_{bs}(t) = \int\limits_{V_{rev}} \frac{F(\theta, \varphi)}{r^2} \frac{S_{bs}(r, \theta, \varphi) b_0^2(\theta, \varphi)}{r^2} e^{-2\beta(r)r} dV, \tag{1}$$

where:

$S_{bs}(r, \theta, \varphi)$—backscattering coefficient,

$\beta(r)$—coefficient of sound attenuation,

$F(\theta, \varphi) = I_P b_N^2(\theta, \varphi)$,

I_P—intensity of the emitted beam along the acoustic axis at a distance of 1 m from the source.

The terms $b_N(\theta, \varphi)$ and $b_0(\theta, \varphi)$ are functions of the directional pattern of the transmitter and receiver, respectively. The problem consists in solving the integral equation (1) and the determination of S_{bs} on the basis of measured I_{bs} values. In order to do this, it is necessary to adopt a number of simplifying assumptions, *viz*:

—the speed of sound in a medium is constant, independent of depth and unchanged by the scatterers (c = const.),

—S_{bs} is independent of a direction of the incident beam,

—the distribution of scatterers in an elementary reverberating volume is uniform,

—scattering is incoherent—reverberation intensity is a sum of intensities originating from the individual scattering centres (energy summation);

—multiple scattering effects, hence also additional absorption of energy, are negligible.

Taking into account the above assumptions, the following expression is obtained:

$$I_{bs}(t) = \frac{I_P S_{bs}(t)}{r^4} \int_{V_{rev}} b_N^2(\theta, \varphi) b_0^2(\theta, \varphi) \, dV. \tag{2}$$

It follows from Figure 1 that an elementary scattering volume is defined in

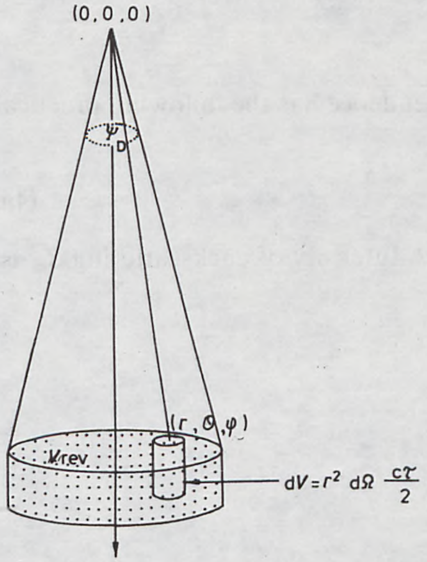

Fig. 1. General scheme of backscattering experiment

terms of unit solid angle $d\Omega$ by the following equation:

$dV = r^2 \, d\Omega \, c\tau/2$,

hence

$$I_{bs}(t) = I_P/r^2 \, S_{bs}(t) c\tau/2\Psi_D, \tag{3}$$

where

$$\Psi_D = \int_0^{4\pi} b_N^2(\theta, \varphi) b_0^2(\theta, \varphi) d\Omega$$

is a resultant solid angle of the transmitter-receiver characteristics.

Expression (3), called sonar equation for volume scattering, describes the dependence of a measured intensity of the signal scattered by inhomogeneities of a medium on the physical parameters of a medium and technical parameters of the measuring system. Measurement of I_{bs} allows the determination of S_{bs}.

A review of acoustic properties of bubbles can be found in numerous papers, particularly in a monograph by Clay and Medwin (1977). Therefore, let us only recall that the acoustic detection of bubbles in water is possible owing to two basic factors, *ie* a contrasting value of acoustic impedance of air with respect to water and resonance. Sound scattering by bubble aggregates is dominated by resonant bubbles of radii:

$$a_R = [1/(2\Pi f)]\sqrt{(3\gamma P)/\varrho}, \tag{4}$$

where:
f – frequency of the incident acoustic wave,
γ – ratio of specific heats of gas,
P – hydrostatic pressure,
ϱ – density of a medium.

In a case of air bubbles in water this dependence has the following practical form:

$$a_R[\mu m] = \{(3280\sqrt{1+0.1z})/f\,[kHz]\}. \tag{4a}$$

This dependence is illustrated in Figure 2. Intensity of backscattering S_{bs} is

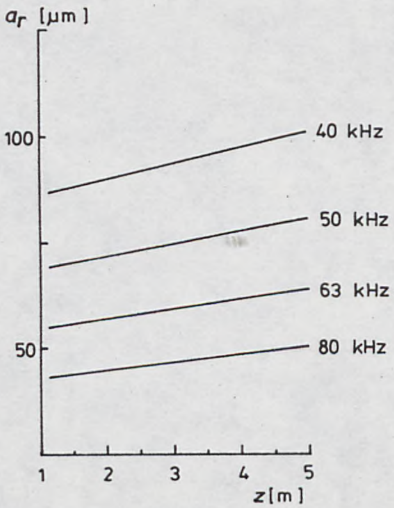

Fig. 2. Depth dependence of resonant bubble radius for frequencies used in the experiment

related to the number of resonant bubbles $n(a_R)$, their size a_R and attenuation constant δ_R (Szczucka, 1986):

$$S_{bs} = [\Pi a_R^3 n(a_R)]/2\delta_R, \tag{5}$$

hence the measurement of S_{bs} at various depths and for various sound frequencies allows determination of the dependence of bubble concentration on the depth and on their size.

3. Results of measurements – dependence of bubble concentration on the depth and bubble size

Acoustic determinations have been carried out at the end of summer season in coastal waters of the Southern Baltic using pulses of the frequencies 40, 50, 63, and 80 kHz, which corresponded to resonant bubbles of radii ranging from 100 to 40 μm. The depth of the sea was equal to *ca* 6 m and the entire depth constituted a mixed layer of almost constant temperature. A general block diagram of the apparatus is presented in Figure 3. Piston transducers, whose directional patterns

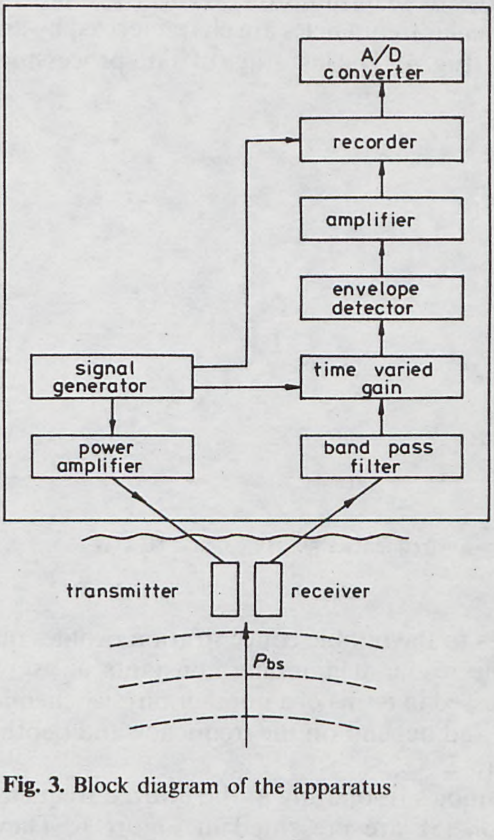

Fig. 3. Block diagram of the apparatus

b_N and b_0 were determined theoretically, have been used as a transmitter and a receiver. The pulse length was equal to twelve periods of the emitted frequency, and hence ranged between 0.15 and 0.30 ms, yielding a spatial length of the pulse in the sea $c\tau/2 = 11-22$ cm. In order to fully utilize the dynamics of the system, the so-called time varied gain has been applied, compensating for a rapid decrease of intensity with the distance ($I_{bs} \simeq 1/r^2$). The collected measurement data has been processed in the following way: analog signals recorded on a tape were sampled at 45 kHz frequency. A hundred pulse sets, each one consisting of

300 samples, have been obtained for each individual measurement. They were subsequently averaged taking into account the time varied gain, which yielded sequences of the normalized voltage values. The length of these sequence has been diversified and in some cases the value of the signal fell below the noise level even for small depths. The sampling frequency (45 kHz) assured a spatial distance between the successive samples $\Delta z = 1.62$ cm (at a mean sound speed in water $c = 1460$ m/s). The spatial length of a pulse $c\tau/2$ was $7-17$ times greater than Δz. Due to a fact that the signal recorded at a given moment contains information on the total energy dissipated in the $c\tau/2r^2 \Psi_D$ volume, it has been necessary to carry out the spatial averaging over the pulse length. Taking into account the parameters dependent on frequency – *ie* source level, hydrophone sensitivity, directivity index, and pulse length – it was possible to determine the vertical profiles of backscattering intensity $S_{bs}(z)$. The particular frequencies are characterized by an almost equal level of scattering intensity (Fig. 4). The last stage of data processing

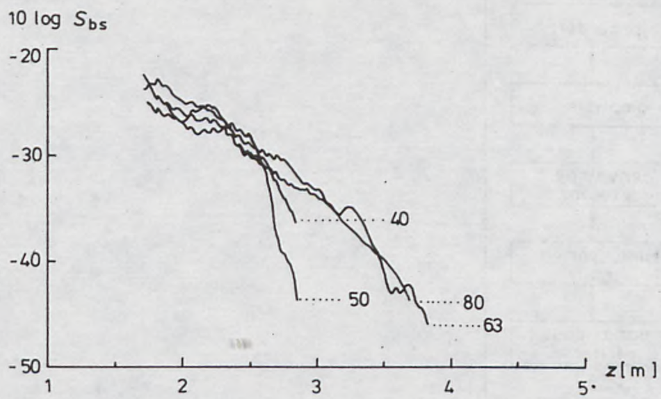

Fig. 4. Vertical profile of backscattering intensity for frequencies 40, 50, 63, and 80 kHz

involves conversion from the S_{bs} profiles to the bubble concentration profiles on the basis of equation (5). Values of the resonant damping constants δ_R were determined numerically. They are expressed in terms of a number physicochemical parameters of the gas and medium and depend on the frequency and depth. This dependence is illustrated in Figure 5.

Final profiles of concentration of bubbles resonating at the utilized frequencies, obtained on the basis of equation (5), are presented in Figure 6. They demonstrate an increase in the number of bubbles with an increase in frequency, and hence with a decrease in the resonant size. The curves describe an exponential decrease in the number of bubbles with the depth (correlation coefficients for such an approximation are equal to $-0.85 - -0.99$).

Choosing the values of $n(f, z)$ for particular frequencies and selected depth levels, it is possible to determine a functional dependence of the number of bubbles both on the depth, and on the bubble size. Approximation by a linear regression method yielded the following relationship:

$$n(a, z) = 2.85 \cdot 10^{11} \cdot a^{-3.64} \exp(-2.42z), \tag{6}$$

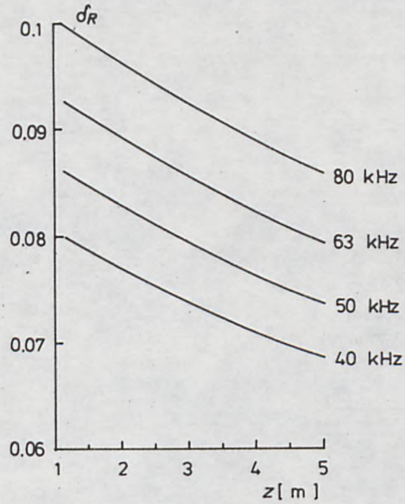

Fig. 5. Depth dependence of resonant damping constant for frequencies used in the experiment

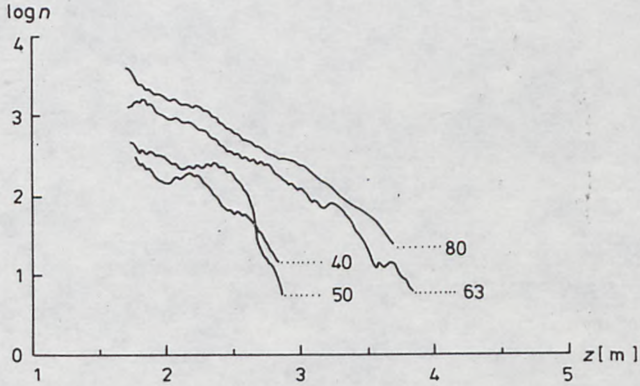

Fig. 6. Vertical profile of a resonant bubble number for frequencies 40, 50, 63, and 80 kHz

where the radius a is expressed in micrometers, the depth z in meters, and $n(a, z)$ is the number of bubbles of radii $[a, a+1\ \mu m]$ in 1 m^3 of water. Figure 7 illustrates this dependence for selected depths.

Figure 8 presents a comparison of the results obtained in the research with the results of other experiments carried out under natural conditions. It can be noticed that the absolute numbers of bubbles differ very significantly (even by a few orders of magnitude), which is quite understandable taking into account that they depend on the local generation conditions. On the other hand, a general trend in the dependence of bubble concentration on their size is very similar in all the papers.

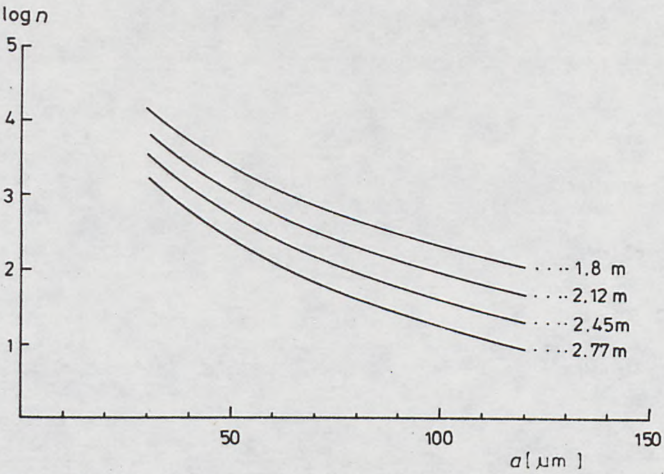

Fig. 7. Bubble size distribution for various depth levels

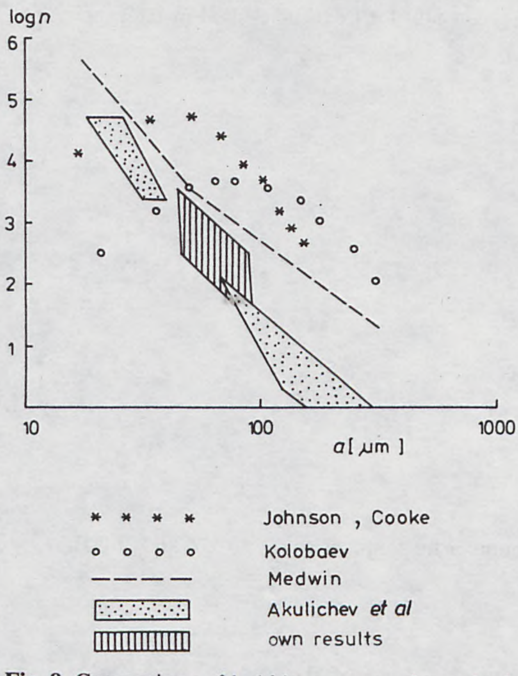

Fig. 8. Comparison of bubble concentrations obtained in various experiments in natural waters

4. Estimation of the effect of bubbles on the acoustic conditions in the Baltic

The obtained experimental concentrations of gas bubbles in the subsurface sea layer have been utilized for numerical modelling of the effect of bubbles on the sound propagation conditions in the Baltic, and particularly for the evaluation of the magnitude of additional attenuation of a vertical acoustic beam, as well as for the determination of changes in sound velocity due to the presence of bubbles (Szczucka, 1986).

In order to determine the attenuation of a vertical beam in a layer of gas bubbles, the expression describing the sound attenuation coefficient S_e is integrated over the entire distance from the source to the target and back:

$$\alpha = 8.68 \int_{z_0}^{z_{max}} S_e(a_R, z)\mathrm{d}z[\mathrm{dB}], \tag{7}$$

where

$$S_e = \frac{2\Pi^2 a_R^3 n(a_R)}{\delta_{rR}};$$

δ_{rR} is resonant damping constant solely due to reradiation.

The lower limit of integration, z_0, is the depth of transducer immersion, while the upper limit, z_{max} cannot be smaller than the thickness of the active layer containing gas inclusions. Assuming various z_0 values, the dependences of the total attenuation along the double distance on the transducer immersion depth have been obtained for various sound frequencies (Fig. 9). It can be noted that

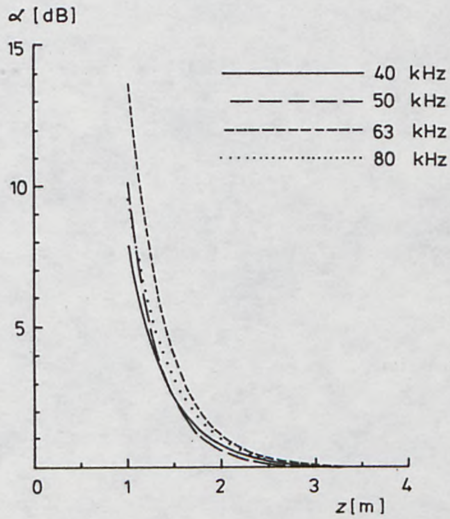

Fig. 9. Dependence of double distance attenuation on transducer immersion depth

localization of the sonic sounder in a layer with bubbles results in additional attenuation of sound of the order of several dB, which can totally invalidate the estimations of biomass, determination of the size of the target, or determination of parameters of the bottom.

To estimate the effect of bubbles on the dispersive properties of the medium, the relationship between the speed of sound in a medium with bublies in terms of the speed of sound in a medium without bubbles, frequency, and bubble concentration was used (Szczucka, 1986):

$$c = c_0 \left\{ 1 - \frac{c_0^2}{2\Pi f^2} \int_{a_{\min}}^{a_{\max}} an(a, z) \frac{(f_R/f)^2 - 1}{[(f_R/f)^2 - 1]^2 + \delta^2} \mathrm{d}a \right\}, \tag{8}$$

where:
c_0 – speed of sound in water without bubbles,
f – incident wave frequency,
f_R – resonant frequency of a bubble of radius a.

Vertical profiles of sound velocity in the surface sea layer in the presence of bubbles were obtained by numerical integration (Fig. 10). For clarity, it has been assumed that $c_0 = 1500$ m/s. The strongest effect was observed at the lowest frequencies, where the change in sound velocity reached a few meters *per* second. This observation is consistent with theory (Clay, Medwin, 1977).

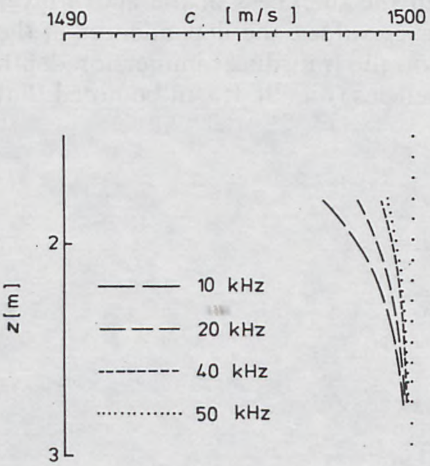

Fig. 10. Influence of bubbles on sound velocity in sea water

5. Recapitulation

The described method of determination of acoustic intensity of backscattering constitutes an unusually straightforward method of the determination of concentration of gas bubbles in water (owing to their specific resonant properties). The number of gas bubbles determined in the Southern Baltic is characterized by an exponential decrease with depth and an exponential decrease with an increase in the bubble size. Similar tendencies have been observed in oceans by other authors. The presence of such number of bubbles influences the speed of sound in the surface layer to a small extent, yet it can radically change the results of vertical acoustic sounding.

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