The influence of crude oil spills on the sea surface on ultrasound scattering

OCEANOLOGIA, No. 31
pp. 107–118, 1991.
PL ISSN 0078-3234

Ultrasound scattering
Rough surface
Statistical distribution
Oil pollution
Remote detection

STANISŁAW J. POGORZELSKI
Environmental Acoustics Laboratory,
University of Gdańsk,
80-952 Gdańsk
ul. Wita Stwosza 57

Manuscript received May 8, 1991 in final form December 30, 1991.

Abstract

The statistical properties of ultrasonic signals scattered by a rough sea surface of clean water and such a surface covered with a spill of petroleum derivatives were examined under open-sea conditions. The results, obtained using a free-drifting light-weight buoylike acoustic system and artificial oil slicks spread over the Baltic Sea surface in preliminary at-sea experiments carried out in calm waters, confirmed the previous laboratory findings and predictions of high-frequency scattering theory. The system allows the movement of the edge of the oil spill to be detected. Simultaneous analysis of all the statistical parameters of the scattered signal distribution may be a starting point for determining the fraction weight of the substance in question, its layer thickness, and the form of oil contamination (monolayer, thick layer or individual dispersed spots).

1. Introduction

The application of acoustic surface-scattering in the remote sensing of sea–atmosphere interactions has become increasingly popular in the last ten years (McConnell, 1983; Stanton and Clay, 1986). It is well known that organic films on the sea surface, of both biogenic and anthropogenic origin, are an important factor affecting the variability of wind-created water waves, particularly short-gravity and capillary waves (Bravo-Zhivotovsky *et al.*, 1984; Ermakov *et al.*, 1986; Wu, 1989).

The present study was motivated mainly by an interest in the acoustic properties of the wave-damping effect caused by organic films of crude oil origin. The acoustic technique offers the opportunity of continuous measurement of water wave-modulating phenomena from beneath the surface to determine the properties of oil spills. Short-gravity and capillary wind-driven waves are steep, whereas their amplitudes are rather small (Schooley, 1958). A directional ultrasonic system of driving frequency high enough to ensure so-called 'high-frequency' scattering conditions, *i.e.* with a large Rayleigh parameter, seems to be the most suitable tool to investigate scattering on a rough surface of the type mentioned (Clay and Medwin, 1977). This is due to the fact that in the light of the high-frequency scattering theory, if the beam geometry and acoustic wavelength are known, the intensity of the scattered signal depends solely on the mean-square slope of the surface irregularities for 'rough surfaces' (Ogilvy, 1987; Tolstoy and Clay, 1966). The same principle is fulfilled in sun glitter (Cox and Munk, 1954) and laser (Lubard *et al.*, 1980) surface probing measurements, where the wavelength of light is smaller than all other wavelengths on the rough surface in question (McConnell, 1983).

The smoothing effect of an oil film on a wind-created surface expresses itself in well-established changes of the statistical parameters of the distribution of an acoustic signal scattered at a rough surface, as already shown in laboratory experiments (Pogorzelski, 1989a, 1989b, 1990).

The aim of this paper is to present a new acoustic system in the form of a free-drifting light-weight buoy for the remote sensing and monitoring of a natural water surface affected by oil pollution. Preliminary results of at-sea experiments carried out by spreading artificial oil slicks over the Baltic Sea surface pointed to the necessity for a comprehensive large-scale experiment with well-defined oil spills of differentiated physicochemical nature, during which both modified sea surface roughness and modification of the signals of various active and passive remote sensors were to be investigated simultaneously. The hypothesis presented in this paper could lead to a practical surveillance system of polluted sea areas.

2. Statistics of acoustic signals scattered by rough surfaces

The principal characteristics of the scattered acoustic signal fluctuations, *i.e.* the autocorrelation functions, the magnitude of signal amplitude variability and the form of the probability density function (p.d.f.) of signal distribution, depend on the value of the Rayleigh parameter R_a defined for specular scattering as (Brekhovskikh, 1974)

$$R_a = 2kh\cos\Theta, \tag{1}$$

where

$k = 2\pi/\lambda$ – the wavenumber of an acoustic wave of length λ,

h – the rms surface wave height,

Θ – the incident angle of the acoustic wave.

The value of R_a also determines the statistics of the scattered signal. At small $R_a (R_a \ll 1)$ the statistical distribution of amplitudes is Gaussian, at large ($R_a \gg 1$) and intermediate values of R_a, the generalized Rayleigh–Rice distribution, gamma, three-parameter lognormal distributions, *etc.* were postulated (Brekhovskikh, 1974; Fortuin, 1970; Horton, 1972; Ogilvy, 1987). The variety of p.d.f.s observed in many laboratory and field experiments results from the different character of the water wave motion in each case, as suggested by Clay *et al.* (1973).

A good approximation of the experimental distribution of acoustic returns is obtained by expanding the Gaussian function $p_n(X_a)$ into a Gram–Charlier series, taking into account statistical moments up to the fourth one (Medwin and Clay, 1970). The p.d.f. polynomial function has the form (Cramer, 1970)

$$p(X_a) = p_n(X_a)\left[1 + \frac{A_1}{6}H_3(t) + \frac{A_2}{24}H_4(t) + ...\right], \tag{2}$$

where

$p_n(X_a)$ – the Gaussian distribution,
$\overline{X}_a, X_a$ – the mean and temporal signal amplitudes,
σ – the standard deviation,
t $= (X_a - \overline{X}_a)/\sigma$ – the normalized random variable,
$H_3(t)$ $= t^3 - 3t$ and $H_4(t) = t^4 - 6t^2 + 3$ – Hermite polynomials,
A_1 $= \mu_3/\sigma^3$ – the assymetry coefficient of distribution (skewness),
A_2 $= (\mu_4/\sigma^4) - 3$ – the flattening coefficient of distribution (kurtosis),
μ_3, μ_4 – the third and fourth central statistical moments.

Parameters A_1 and A_2 describe in a regular way the deviations of the experimental distribution from the normal one, in which values of $\overline{X}_a$ and σ are introduced from the experimental data. The fluctuation coefficient η is the measure of signal amplitude variability and is defined as (Brekhovskikh, 1974)

$$\eta = \frac{\sigma}{\overline{X}_a}. \tag{3}$$

The statistical parameters $\overline{X}_a, \eta, A_1$ and A_2 were chosen for further considerations.

3. Instruments and method

Studies of the effect of an artificial oil slick on the statistics of ultrasonic signals scattered from a rough sea surface were carried out in October 1989 on the Baltic from aboard a platform built on piles about 200 m off Gdynia at a depth of 7–15 m.

The acoustic system – a free-drifting, lightweight buoy – has already been applied in remote sensing and monitoring of polluted sea waters (Pogorzelski, 1990). A block diagram of the measuring set-up and associated electronics is presented in Figure 1. The transmitting (T) and receiving (R) ultrasonic quartz transducers are placed on the H-shaped support (8) of the free-drifting buoy and submerged 10 cm beneath the surface. Two float wings (6) enable self-orientation of the buoy according to the wind direction, which significantly reduces the influence of surface water waves reflected from the supporting floats (7) on the measurement. The *c.* 5 kg buoy is also equipped with balancing floats (9) and devices for fixing and accurately orienting the transducers (10).

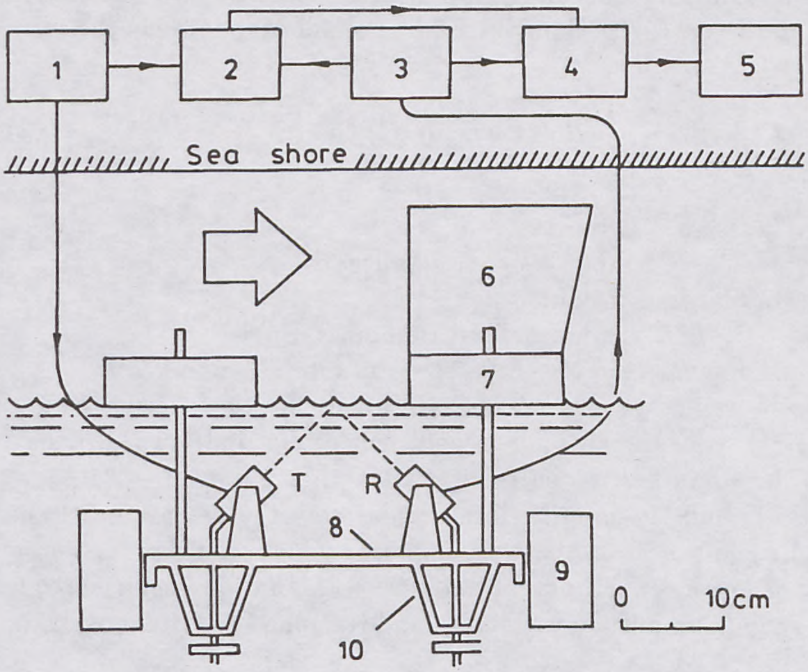

Fig. 1. Diagram of the experimental set-up and the associated electronics

The electronic part of the system is located on the platform and connected to the buoy with cables. As shown in Figure 1, the acoustic system is based on 'high-frequency' and specular geometry scattering. The ultrasonic transmitter (1) operating under a pulse regime with a 3 kHz repetition frequency produces series of pulses lasting a few microseconds. Each pulse has a rectangular envelope and is filled with a sine wave of 10 MHz frequency. The acoustic projector has a 3° half-power bandwidth at a carrier frequency of 10 MHz. The incident angle of the ultrasonic beam ranges from 40° to 60°. The scattered signal is recorded in the specular direction ($\Theta = 45°$). An oscilloscope (2) is used for visual inspection and transducer adjustment after amplification by an ultrasonic receiver (3). This acoustic system provides 'high-frequency' scattering with a Rayleigh parameter of the order of about 100. The time gate in the electronic circuit (4) enables the envelope and peak values of only that part of the signal due to surface scattering to be detected. Then the fluctuations of the signal peak value X_a are statistically analyzed using a statistical distribution analyzer (5) (Type 4420, Brüel & Kjaer), which measures the signal amplitude peak value every 0.1 s. The p.d.f. of the distribution was determined on the basis of 1800 counts.

The scattering measurements were done on a clean water surface (control) and surfaces covered with films of a variety of petroleum derivatives. Three such commercially available derivatives – heavy gear oil, Selectol, and gasolines – were applied as artificial slick-forming materials in open-sea measurements. In order to characterize the spreadability of these substances, the following physical properties were additionally measured: density, surface tension, and the interfacial tension in contact with sea water collected from the measuring area.

It is well known that oil placed upon a water surface will spread by surface tension if the spreading coefficient $S_{o/w}$ is positive. It is the net surface tension available that induces the spreading (Adamson, 1982)

$$S_{o/w} = \gamma_w - \gamma_o - \gamma_{o/w}, \tag{4}$$

where

γ_w, γ_o – the respective surface tensions of water and oil substance,

$\gamma_{o/w}$ – the oil/water interfacial tension.

A positive value suggests the ability of an oil substance to form on a water surface a coherent bulk film with a thickness ranging from monomolecular to one, depending on the amount of the liquid and the surface area available. Many oils, including heavier hydrocarbons, have negative spreading coefficients and will not spread on water, and appear to form lenses surrounded by a monolayer. The equilibrium thickness of the lens d_o is determined from (Adamson, 1982)

$$d_o^2 = -\frac{S_{o/w}\rho_w}{g\rho_o(\rho_w - \rho_o)}, \tag{5}$$

where

ρ_w, ρ_o – respective densities of water and oil substance,

g – the acceleration due to gravity.

The results of the supplementary measurements, obtained by a procedure described in detail elsewhere (Pogorzelski *et al.*, 1986), are presented in Table 1. Gasolines (light petroleum derivatives) turned out to have a positive spreading coefficient with respect to sea water and spontaneously formed uniform slicks. On the other hand, Selectol – a heavy, viscous gear oil – had a negative value of $S_{o/w}$ and appeared to form on the sea surface

Table 1. Physical properties of slick-forming substances and their spreadability in contact with sea water from the measuring field at 286 K

Substance	ρ [kg m^{-3}]	γ [10^{-3} N m^{-1}]	$\gamma_{o/w}$ [10^{-3} N m^{-1}]	$S_{o/w}$ [10^{-3} N m^{-1}]	d_o [cm]
Gasoline 94	760.2	20.3	26.3	+6	–
Extraction gasoline	773.4	22.4	25.7	+4.5	–
Selectol	880.4	35.9	24.2	–7.5	0.27
Sea water	998.8	52.6	–	–	–

uniform layers or discrete lens-shaped blobs of various diameters, with an equilibrium thickness d_o of 0.27 cm.

This report deals with the study of small film slicks when the sea is calm at a wind velocity of $V = 2 \pm 0.5$ m $\cdot$ s^{-1} measured at a height of 3 m using a standard cup anemometer. The slick size measured from the edge of the spot exposed to the wind up to the measuring point, was of the order of 7–10 m. From a distance, the film's presence could be detected visually only from its surface smoothing effect.

The persistence of films was quite variable, being a function of current, wind and wave action, as well as the accuracy of the initial slick deposition from a hexane oil substance solution. Slick duration varied between 30 to 100 min., decreasing as expected with increasing sea state. The p.d.f.s of the signal fluctuations were recorded 7–10 times for all the film-covered surfaces and an average dependence then adopted for further considerations. Data obtained for a clean surface were taken to be control data.

4. Results and discussion

Figure 2 presents an example of the p.d.f. for a sea water surface covered with a Gasoline 94 film, measured at a wind speed of 2 ± 0.5 m $\cdot$ s^{-1}. Also included are two theoretical forms of p.d.f.s., *viz.* Rayleigh (solid line) and Gaussian (dotted line), in which the values of $\overline{X}_a$ and σ emerge from the experimental data. In order to make the comparison between the experimental and theoretical dependences easier, they are presented as functions of the normalized random variable t. It has been found that the experimental points in the case of all the film-coated surfaces under study are much closer to the Rayleigh curve than to the Gaussian one. This is in agreement with the results of numerous authors and the predictions of the 'high -frequency' scattering theory (Clay *et al.*, 1973; Ogilvy, 1987; Stanton and Clay, 1986), and has been already confirmed by the χ^2 goodness of fit test by the author (Pogorzelski, 1990). One may conclude that the presence of an oil film does not significantly affect the form of the p.d.f., although it does lead to noticeable changes in the statistical parameters of signal distribution as compared to the scattering of a clean sea surface.

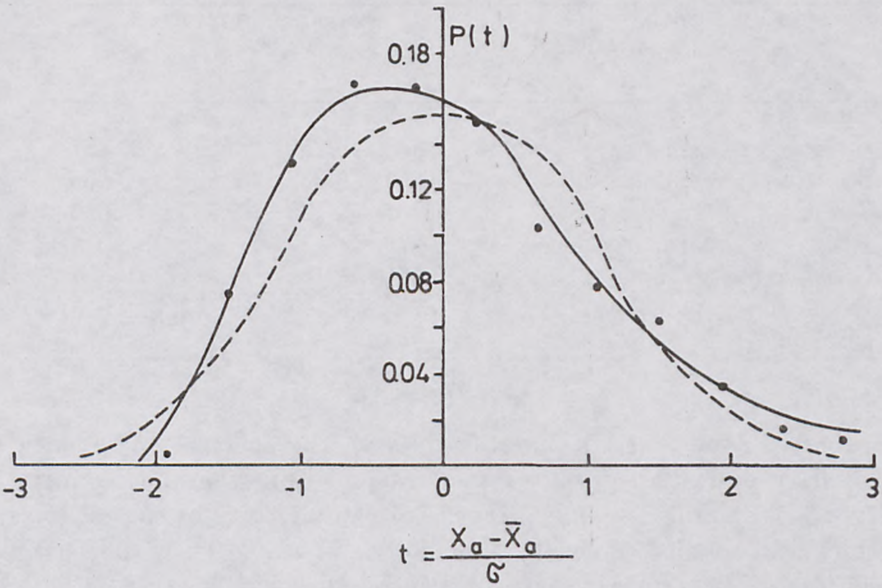

Fig. 2. Theoretical and experimental probability distributions of amplitudes of ultrasonic signals scattered from the Baltic Sea surface covered with a Gasoline 94 film. Experimental points (•), theoretical Rayleigh (—) and Gaussian (- - -) functions, in which parameters $\overline{X}_a$ and σ emerge from the experimental data

The values of the parameters for the clean water case were chosen as a reference. The statistical parameters for a variety of film-coated sea surfaces, averages of 7–10 recordings, are set out in Table 2. This shows that for light crude oil derivatives (gasolines) the mean amplitude is higher and the fluctuation coefficient is lower, and that the distribution is more symmetrical ($|A_1|$ lower) and sharper (A_2 positive), in comparison the clean surface values. Heavier oil fractions increase the mean amplitude and intensify the flattening of the distribution ($|A_2|$ larger), leaving the η and A_1 parameters almost unchanged. The variability in the statistical parameters of a surface covered with oil slicks in the form of artificial, small dispersed lenses, is quite different (see 3 in Tab. 2). The mean amplitude and fluctuation coefficient are lower, and a slight symmetrization (A_1 is closer to zero) with a strong peak (positive A_2 value) of the distribution may be encountered. These results suggest that the statistics of the scattered signal are affected by the structural form of the oil substances rather than their physical properties. In order to propose a conceivable explanation of the phenomenon observed, let us consider the damping effect on wind-generated waves by a crude oil spill floating on the sea surface.

Table 2. Statistical parameters of the signal distribution versus the characteristics of film-covered surfaces

Data set	Substance	Slick structure	Statistical parameters			
			$\overline{X}_a$ [V]	η	A_1	A_2
1	Clean sea surface		0.168	0.355	0.649	-0.357
2	Selectol	uniform thick layer	0.181	0.338	0.605	-0.495
3	Selectol	small artificial dispersed lenses	0.135	0.278	0.543	2.686
4	Gasoline 94	monolayer	0.178	0.186	0.384	0.314
5	Extraction gasoline	monolayer	0.232	0.115	-0.102	0.519

According to Alpers and Hühnerfuss (1988), the spectral energy density of capillary and short-gravity water waves within the thick mineral oil layer zones is modified mainly because of the viscosity of the oil layer and its thickness, as also shown by Pogorzelski *et al.* (1986). The damping coefficient α of a surface wave of wavenumber k follows the k^2 law (Wu, 1989). The 'holes' between the thick patches covering the sea surface are filled with a surface-active material and/or a mixture of surface-active compounds plus mineral oil compounds (Hühnerfuss, personal communication). Such surface-active substances are always encountered in crude oil as 'impurities' or detergent additives in engine oils, in particular in 'weathered' crude oils. They tend to spread very easily from the thick oil spill centres over the surrounding sea surface. Within the sea surface area covered by these monomolecular organic films, surface tension gradients and thus Marangoni wave damping can be induced on a rough surface. The result is the resonance-like behaviour of the damping coefficient α as a function of the surface wave frequency f. The $\alpha(f)$ dependence attains a maximum in the frequency range 3–20 Hz *i.e.*, for capillary and short-gravity water waves, depending on the viscoelastic properties of the spread film (Alpers and Hühnerfuss, 1988; Ermakov *et al.*, 1986). Generally, the presence of oil films suppresses wind-generated waves, although the opposite effect may be observed on waves decimeters in length, which are accordingly amplified (Bravo-Zhivotovsky *et al.*, 1984).

As a consequence, two zones exhibiting different mechanisms of wave attenuation can be specified within a mineral oil spill. Because of this, a more realistic statement on the relationships between the surface film properties and the scattered signal statistics must await a more precise method of *in situ* surface film characterization. Work on this is in progress.

Figure 3 presents a time record of the scattered signal amplitude X_a. The passage of the Gasoline 94 slick edge over the area of ultrasound scattering is expressed by a rapid drop in the signal level.

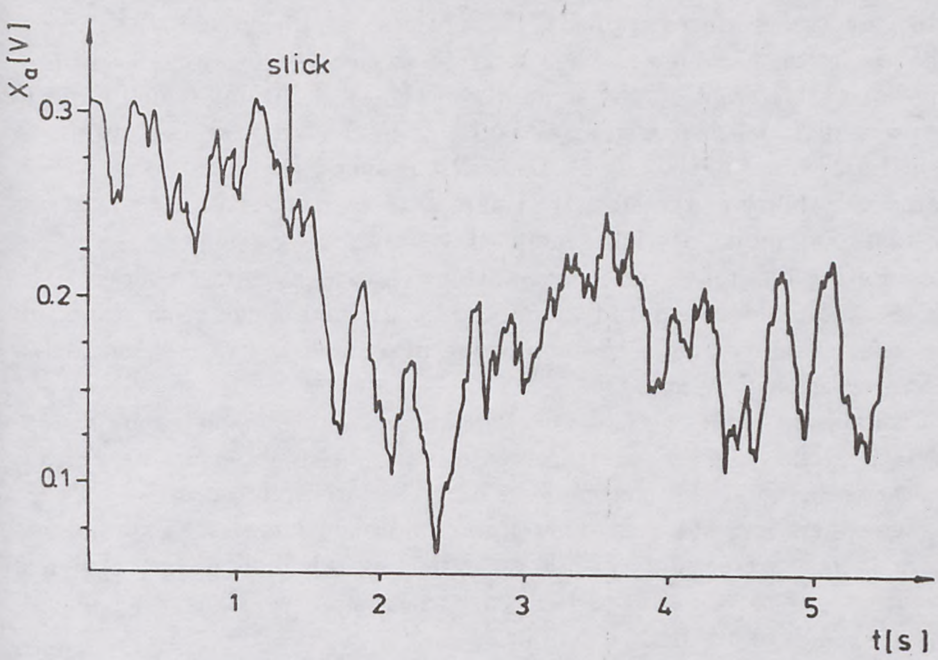

Fig. 3. A time record of the scattered signal amplitude. The arrow indicates the passage of a monomolecular Gasoline 94 film

One of the conceivable explanations could be the smoothing effect of capillary and short-gravity water waves playing a principal role in Marangoni-type damping by viscoelastic films. As stated above, these low-amplitude but steep waves, present on the sloping faces of long gravity waves, play the most important role in 'high-frequency' acoustic scattering (Ogilvy, 1987).

On the other hand, an oil spill not only influences the dissipation rate of wind-generated waves, but also affects the aerodynamic factors describing the wind-surface interaction process, as mentioned in Pogorzelski (1990). In addition, the dynamics of the acoustic returns is also attributed to the directional system features, *i.e.* the ratio of the linear dimension of the irradiated surface area to the length of surface water waves from the range to be studied. It seems that in contrast to Cox and Munk (1954), which dealt with a viscous oil layer, the water surface coated with a light gasoline film of low surface tension and viscosity (see Tabl. 1) could have been more susceptible to deformation by wind action. Unfortunately, a more detailed explanation will not be forthcoming until simultaneous analyses of the statistics of a rough sea surface and its *in situ* properties are done.

5. Concluding remarks

The presence of an oil film does not significantly change the form of the p.d.f., which followed the Rayleigh distribution for all the clean and film-covered sea surfaces studied. The noticeable differences in the values of the statistical parameters when referred to clean-surface scattering probably have their origin in the structure of the oil pollutant (thick uniform oil layer, individual dispersed small lenses or monolayer) rather than in the physical properties of the oil substances. It is suggested that the very complicated variability of the statistical parameters can be explained in terms of the damping model of wind-generated waves by an oil spill having two zones exhibiting different surface wave attenuation mechanisms therein. The acoustic system described and the methodology introduced seem to be suitable for continuous long-term monitoring of oil spills on the sea surface in inshore regions at low sea states.

A reliable acoustic method for oil pollution determination requires careful and extensive *in situ* measurements of the air-sea interface properties, and other environmental factors describing the interaction process between the atmosphere and the sea. Therefore comprehensive at-sea experiments with artificial surface films of differentiated, well-defined physicochemical structure ought to be performed in order to develop remote sensing techniques for studies of oil slick behaviour.

Acknowledgements

The author wishes to thank Professor R. Cini and Professor G. Loglio and co-workers (University of Florence, Italy), and Professor H. Hühnerfuss and Dr. P. Lange (University of Hamburg, Germany) for stimulating and enlightening discussions.

The author is also grateful for the Individual Mobility Grant (Contract No. IMG–PLT–0143–90) provided by the European Community's Tempus programme.

References

Adamson A. W., 1982, *Physical chemistry of surfaces*, Wiley, New York.

Alpers W., Hühnerfuss H., 1988, *Radar signatures of oil films floating on the sea surface and the Marangoni effect*, J. Geophys. Res., 93, C4, 3642–3648.

Bravo-Zhivotovsky D. M., Dolin L. S., Ermakov S. A., Zuykova E. M., Luchinin A. G., Titov V. I., 1984, *The effect of the amplification of decimetre wind waves in the region of an oil slick*, Dokl. Akad. Nauk SSSR, 276, 1243–1246.

Brekhovskikh L. M., 1974, *Akustika okeana*, Nauka, Moskva.

Clay C. S., Medwin H., 1977, *Acoustical Oceanography: Principles and applications*, Wiley, New York.

Clay C. S., Medwin H., Wright W. M., 1973, *Specularly scattered sound and the probability density function of a rough surface*, J. Acoust. Soc. Am., 53, 1677–1682.

Cox C. S., Munk W. H., 1954, *Statistics of the sea surface derived from sun glitter*, J. Mar. Res., 13, 198–227.

Cramer H., 1970, *Random variables and probability distributions*, Cambridge University Press, 3, Chapter 4, New York.

Ermakov S. A., Zuykova E. M., Panchenko A. R., Salashin S. G., Talipowa T. G., Titov V. I., 1986, *Surface film effect on short wind waves*, Dyn. Atmos. Oceans, 10, 31–50.

Fortuin L., 1970, *Survey of literature on reflection and scattering of sound waves at the sea surface*, J. Acoust. Soc. Am., 47, 1209–1228.

Horton C. W., 1972, *A review of reverberation, scattering and echo structure*, J. Acoust. Soc. Am., 51, 1049–1061.

Lubard S. C., Krimmel J. E., Thebaud L. R., Evans D. D., Shemdin H., 1980, *Optical image and laser slope meter intercomparisons of high-frequency waves*, J. Geophys. Res., 85, 4996–5002.

McConnell S. O., 1983, *Remote sensing of air-sea interface using microwave acoustics*, Proc. Oceans IEEE, 1, 85–92.

Medwin H., Clay C. S., 1970, *Dependence of spatial and temporal correlation of forward-scattered underwater sound on the surface statistics*, II Experiment, J. Acoust. Soc. Am., 47, 1419–1429.

Ogilvy J. A., 1987, *Wave scattering from rough surfaces*, Rep. Prog. Phys., 50, 1553–1608.

Pogorzelski S. J., 1989a, *Detection of oil-derivative contamination of water surface by statistical analysis of scattered acoustical signals*, J. Acoust. Soc. Am., 85, 2383–2387.

Pogorzelski S. J., 1989b, *Statistics of underwater acoustic signals scattered by the rough water surface covered with a layer of oil substances*, Oceanologia, 27, 45–60.

Pogorzelski S. J., 1990, *Remote sensing of the sea oil pollution by means of high-frequency surface scattering*, Arch. Acoust., 15, 437–446.

Pogorzelski S. J., Linde B., Śliwiński A., 1986, *An influence of the oil-derivative layer thickness on the capillary surface wave absorption*, Oceanologia, 24, 41–46.

Schooley A. H., 1958, *Profiles of wind-created water waves in the capillary-gravity transition region*, J. Mar. Res., 16, 100–108.

Stanton T. K., Clay C. S., 1986, *Sonar echo statistics as a remote sensing tool: volume and seafloor*, J. Ocean Eng. IEEE, OE–11, 79–96.

Tolstoy I., Clay C. S., 1966, *Ocean acoustics*, McGraw-Hill Book Comp., New York.

Wu J., 1989, *Suppression of oceanic ripples by surfactant- spectral effects deduced from sun glitter, wave staff and microwave measurements*, J. Phys. Oceanogr., 19, 238–245.