Detection of oil derivative substances on a sea surface by statistical analysis of scattered acoustic signals*

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Scattering of acoustic signals
Statistical analysis
Water pollution
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Abstract

The statistical amplitudes of ultrasonic signals scattered from clean sea surfaces and surfaces contaminated by crude oil films with different *in situ* physical properties are described by means of the probability density function of the scattered signal amplitude distribution. The scattered signals data in specular geometry were collected at a carrier frequency of 10 MHz. The fluctuation coefficient η – a measure of the signal amplitude variability – and the parameters A_1 and A_2 – the asymmetry and flattening coefficients – describe the deviation of the statistical distribution from the normal in the presence of oil films and are referred to those coefficients obtained from clean surface scattering.

1. Introduction

Experimental investigations of the scattering of an acoustic beam from a rough surface statistically described by its r.m.s. roughness, height standard deviation (h.s.d.) and probability density function (p.d.f.) has been much discussed (Clay and Medwin, 1970; Clay *et al.*, 1973; Medwin and Clay, 1970; Welton *et al.*, 1972). Pogorzelski *et al.* (1988) investigated the scattering of high frequency acoustic waves from a water surface covered with oil films and they studied these statistical parameters on the basis of laboratory measurements (Pogorzelski, 1989, 1989a).

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The capillary surface waves generated produced a random surface, and the acoustic signal scattered by the surface was also of a random nature. This can be described quantitatively by means of the statistical moments of the signal amplitude distribution. The scattered coefficient of acoustic waves under such conditions depends on the mean square slope of the surface (Clay and Medwin, 1970; Clay *et al.*, 1973; Medwin and Clay, 1970). The presence of an oil film on the sea water surface alters the damping mechanism of the propagation waves, particularly for short surface waves.

The statistical parameters chosen for discussion in this paper when ultrasonic signals are scattered from clean sea surfaces and surfaces contaminated with oil derivative films with different *in situ* properties are the following: $\bar{a}$ – the mean amplitude, η – the fluctuation coefficient, A_1 – the asymmetry coefficient, A_2 – flattening coefficient (Pogorzelski, 1989a, 1990a,b).

2. The statistical parameters of an acoustic signal scattered at a rough surface

A rough surface is described by a statistical statement of the root mean square (r.m.s.) roughness; the probability density function (p.d.f.) and the statistical correlation function of surface heights (Marsh *et al.*, 1961; Ogilvy, 1987). The first order of the probability density function of a random surface is assumed to be Gaussian.

The significant characteristics of the fluctuations of the scattered acoustic signal, *i.e.* the auto-correlation function, the magnitude of amplitude fluctuations and the form of the probability density function, depend on the value of the Rayleigh parameter (Clay and Medwin, 1970, 1977; Medwin and Clay, 1970)

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

where

$k = 2\pi/\lambda$ – the wave number of the acoustic wave,
h – height of surface irregularities,
θ – incident angle of the acoustic wave.

The probability density function of the resultant acoustic wave amplitude (a) was developed by Rayleigh for $R_a \gg 1$. In practice, the high distribution is assumed to be non-linear or Gaussian, in accordance with the following expression (Beckmann and Spizziching, 1963; Marsh *et al.*, 1961; Pogorzelski *et al.*, 1986; Pogorzelski, 1990a; Welton *et al.*, 1972):

$$p(a) = \frac{a}{\sigma^2}\exp -a^2/2\sigma^2. \tag{2}$$

For $R_a \ll 1$ the surface is relatively smooth, the statistical distribution signals have a Gaussian $P_G(a)$. The specular scattered relative pressure amplitude will yield a Gaussian probability density function of the form (Leonard, 1970; Medwin, 1967; Welton *et al.*, 1972)

$$P_G(a) = \frac{1}{(2\pi)^{1/2}\sigma} \exp -a^2/2\sigma^2. \tag{3}$$

The consequence of the non-linear properties of the sea surface can be accounted for as the participation of the consecutive terms of the Gram-Charlier series of the surface elevation statistical density function (Clay and Medwin, 1964, 1970; Clay *et al.*, 1973; Medwin and Clay, 1970)

$$p(a) = (2\pi m_2)^{1/2} \exp -\sigma^2/2 \left[1 + \frac{m_3 H_3}{3} \frac{m_4 H_4}{12} + \cdots\right], \tag{4}$$

where

H_3 and H_4 – are third and fourth degree Hermit polynomials given in the following forms:

$$H_3 = \sigma^3 - 3\sigma,$$
$$H_4 = \sigma^4 - 6\sigma^2 - 3, \tag{4a}$$

where σ is the standard deviation computed from experimental data, and m_2, m_3, m_4 are the second, third and fourth central statistical moments respectively.

A good approximation of the experimental distribution is obtained by expanding the Gaussian distribution into the Gram-Charlier series up to the fourth statistical moment. The probability density function of the polynomial distribution has the following form (Clay, 1966; Clay and Medwin, 1964; Clay *et al.*, 1973; Medwin and Clay, 1970; Pogorzelski, 1989a):

$$P(a) = \left[1 - \frac{1}{6} A_1 H_3 + \frac{1}{24} A_2 H_4(m)\right] \left[\frac{1}{(2\pi)^{1/2}\sigma} \exp\left(-a^2/2\sigma\right)\right], \tag{5}$$

where

$A_1 = m_3/\sigma^3$ – the asymmetry coefficient,
$A_2 = m_4/\sigma^4 - 3$ – the flattening coefficient,
$m = \bar{a}/\sigma$ – a normalized random variable.

Parameters A_1 and A_2 can be described in a non-regular manner as the deviation of the experimental distribution from the Gaussian one in which the mean amplitude and the standard deviation are introduced from experimental data.

The fluctuation coefficient is a measure of the signal amplitude variability and is defined by (Clay and Medwin, 1977; Pogorzelski, *et al.*, 1988; Pogorzelski, 1989, 1989a)

$$\eta = \frac{\sigma}{\bar{a}}, \tag{6}$$

where
$\bar{a}$ – the mean amplitude.
The intensity of the acoustic signals is given by the acoustic pressure and the voltage amplitude of the scattering signal (Clay and Medwin, 1964; Marsh *et al.*, 1955)

$$< I_s >\sim< P_s >\sim A^2. \tag{7}$$

At a high frequency range, the scattering function of acoustic waves depends only on the mean square slope of the surface. However, the intensity of scattered high-frequency signals depends on the slope of surface irregularities; the specular forward scattering is expressed by

$$< I_s >=< PP^* >\sim \frac{1}{(h/\lambda)^2}. \tag{8}$$

3. Experimental conditions

The measurements were performed in the Naval Port, Gdynia, using 10 MHz ultrasonic signals. The block diagram of the experimental arrangement is shown in Figure 1.

The transmitting T and receiving R ultrasonic quartz transducers were situated on the supports of a free floating buoy at a depth of about 6 cm below the sea surface. The horizontal distance between the two transducers was about 13 cm.

The electrical part of the set-up was located on the sea shore and connected to the buoy by 50 m cables. The ultrasonic transducer operated under water with pulses in a frequency regime of 3 KHz repetition and produced a series of pulses lasting several microseconds. The incident angle of the acoustic beam was 60° and signals scattered from the surface were recorded in a specular direction from the clean and contaminated sea surfaces. To obtain the probability density function of the amplitude fluctuation, the signals were tape-recorded as 200 second segments of the acoustic wave using a level Brüel & Kjaer 7003 recorder. The sea-level wind velocity was measured with an anemometer for each film-covered surface. The wind velocity, which was nearly constant, is given in Table 1 for both clean and oil-covered surfaces. During the measurements the sea temperature was 285 K and the air temperature above the water was 284.5 K. The recorded acoustic signal segments were played back using a Brüel & Kjaer 4420 statistical distribution analyser, which measured the amplitude every 0.1 second when a generator produced short pulses, each of which could cause the counter, or counters, to register one more digit. Every pulse was recorded by the Period Counter (total register), and at the same time, by the 12 channel counters when the total count number N was distributed in 12 channel counts, *i.e.*

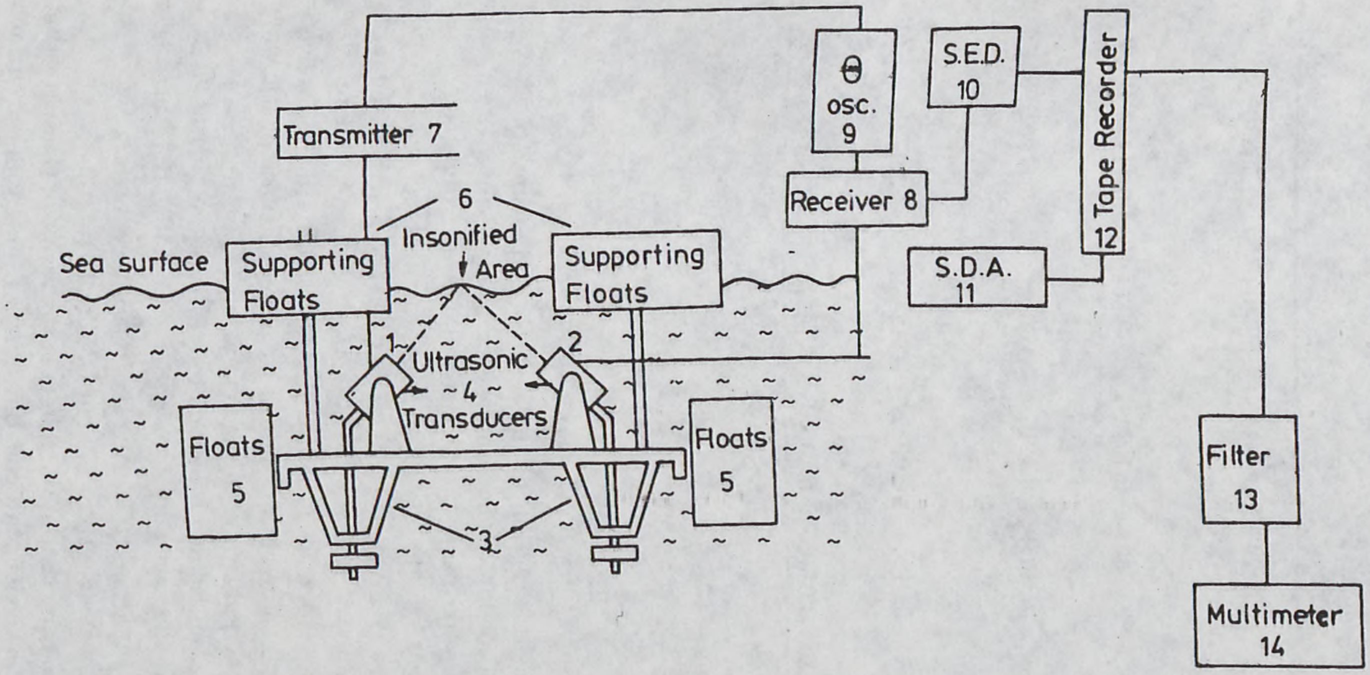

Fig. 1. Block diagram of the experimental set-up. 1, 2 – ultrasonic quartz transducers, 3 – devices for fixing and orienting the transducers, 4 – H-shaped support, 5 – balancing floats, 6 – supporting floats, 7 – ultrasonic transmitter, 8 – ultrasonic receiver, 9 – oscilloscope, 10 – time gate + signal envelope and peak value detectors, 11 – Brüel & Kjaer 4420 statistical distribution analyser, 12 – Brüel & Kjaer 7003 tape level recorder, 13 – analogue tunable band–pass filter, 14 – Unipan 543 digital multimeter

Table 1. The statistical parameters measured for a clean sea surface and one covered with oil films under natural conditions

Oil substance	$\bar{a}$	σ $m_2 = \sigma^2$	$\sigma = \frac{\sigma}{\bar{a}}$	$A_1 = \frac{m^3}{\sigma^3}$	$A_2 = \frac{m^4}{\sigma^4}$ - 3	Wind speed [u, m · s
Clean sea surface	0.11377	0.01746	0.15349	0.8402	0.55336	1.7
Selectol plus oil	0.11386	0.07897	0.15717	0.66861	0.11169	2.0
Contamination sea surface	0.10568	0.01279	0.12102	0.30140	-0.17951	2.3
Gasoline 86 film	0.13255	0.01214	0.09159	-0.12459	-0.16701	2.0
Gasoline 94 film	0.01123	0.01165	0.10374	0.15574	-0.211438	2.2

σ – standard deviation,
$\bar{a}$ – mean amplitude,
η – fluctation coefficent,
A_1 – skewness coefficient,
A_2 – peakedness coefficient.

$$N = N_1 + N_2 + N_3 + \cdots + N_{12}. \tag{9}$$

The probability density function of the signal distribution was measured on the basis of 1800 counts. The samples were sorted into 12 channel amplitude high analysers to obtain the acoustic signal distribution.

The ultrasonic beam generated by a directional transducer with narrow characteristics irradiated a given surface area (A). The irradiated area formed an elliptical slope of $A = \pi XY = 0.645 \cdot 10^{-4}$ m^2, where $X =$ 1.3 cm and $Y = 0.6$ cm (Pogorzelski, 1989a). In order to obtain the Rayleigh parameter value, the local value of the angle of incidence of the acoustic wave and the surface height were introduced into equation (1).

In this investigation the Rayleigh parameter R_a is equal to $106.08 \gg 1$ when the wavelength of the acoustic signals $\lambda = \frac{c}{f} = 1.48 \cdot 10^{-4}$ m, assuming that $c = 1480$ m $\cdot$ s^{-1} and $f = 10^7$ Hz. Capillary surface waves of frequency 30 Hz have a wavelength of 1.2 cm (Willard, 1959).

The large Rayleigh parameter obtained here is the result of the scattering of high-frequency, short wavelength acoustic signals from capillary surface

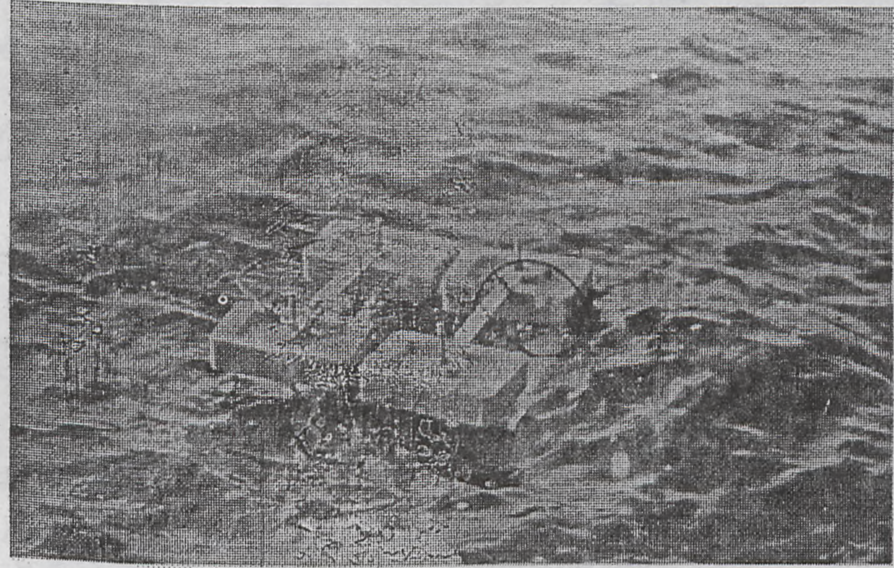

Fig. 2. The platform used in the experiment under natural conditions

waves. The scattering measurements were carried out for both clean sea surfaces and surfaces covered with a layer of Gasoline 94, Gasoline 86, second hand engine oil (Selectol plus) and a surface contaminated *in situ*.

The oil substances were dissolved in hexane before being spread onto the sea surface; the film moved along with the surface water flow. The platform used in this investigation is shown in Figure 2.

4. Results and discussion

The coefficients A_1 and A_2 describe in a regular manner deviations of the experimental distribution from the theoretical Gaussian one, in which the main amplitude $\bar{a}$ and the standard deviation σ were introduced from experimental data (Pogorzelski, 1990a,b, 1991). The statistical parameters of the scattered acoustic signal distribution from the clean sea surface and the oil-covered surface were recorded under natural conditions (Tab. 1).

The spectral range of the signal fluctuations is linked with the properties of the acoustic system used, especially with the ratio of the irradiated surface area to the length of the surface waves. Figures 3, 4, 5, 6 depict examples of probability distributions $P(a)$ of amplitudes of acoustic signals scattered from clean and oil-covered sea surfaces. In order to facilitate the comparison between the experimental and theoretical distributions, both the main

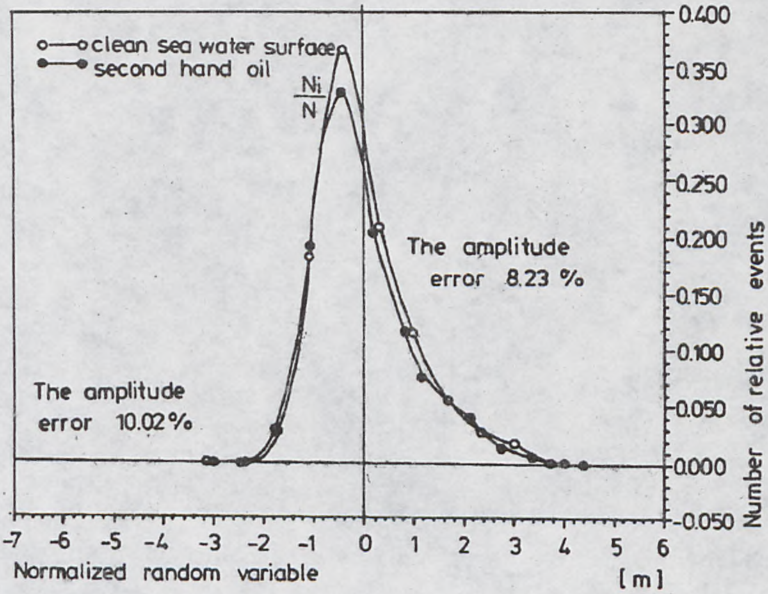

Fig. 3. Normalized probability density function of a clean sea water surface and in the presence of a Selectol plus oil film in the open sea, measured by acoustic signal scattering in the Gulf of Gdańsk

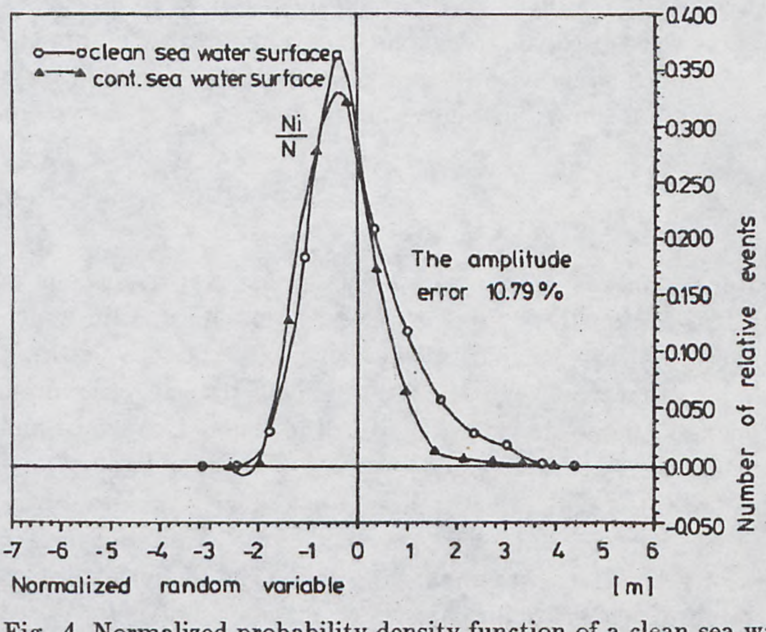

Fig. 4. Normalized probability density function of a clean sea water surface and a contaminated one under natural conditions, measured by acoustic signal scattering in the Gulf of Gdańsk

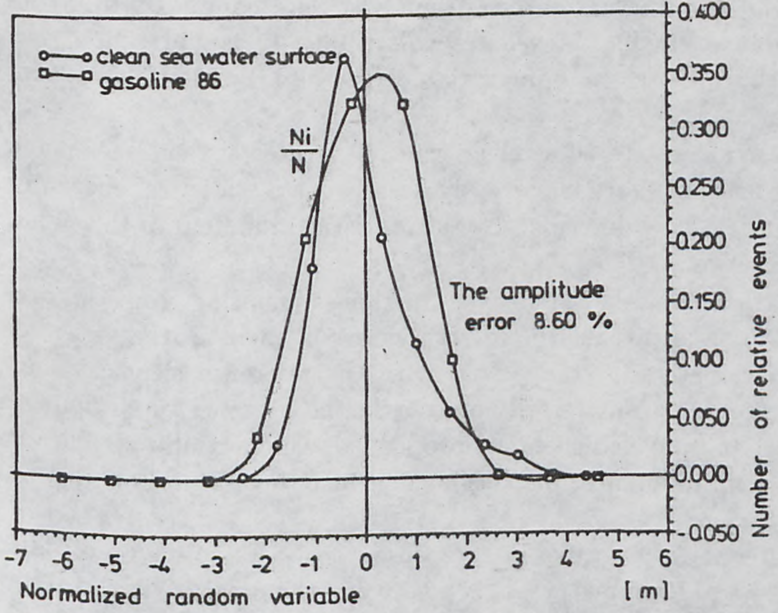

Fig. 5. Normalized probability density function of a clean sea water surface and one covered with a Gasoline 86 oil film under natural conditions, measured by an acoustic method in the Gulf of Gdańsk

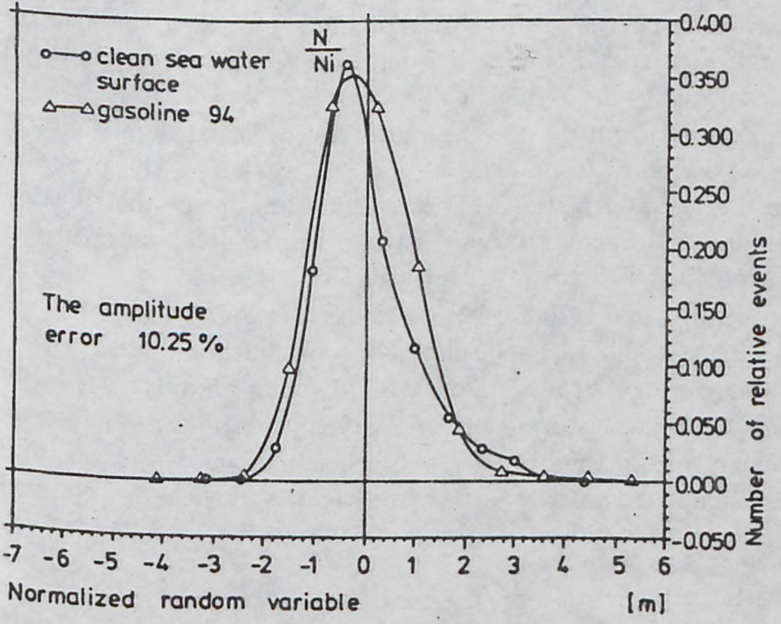

Fig. 6. Normalized probability density function of a clean sea water surface and one covered with a Gasoline 94 oil film under natural conditions in the Gulf of Gdańsk

amplitude ($\bar{a}$) and the fluctuation coefficient (η) were computed from the experimental data, and the signal distribution is presented as a function of a normalized random variable (see also Pogorzelski, 1990a, 1991).

An acoustic signal scattered at clean and oil-covered sea surfaces made rough by the presence of short surface waves is of such a statistical character that can be quantitatively described by the statistical moment of the signal amplitude distribution.

The systematic change in sea surface roughness resulting from the presence of the oil films is revealed in corresponding changes in the values of the statistical parameters in comparison with the reference clean sea surface. Table 1 presents parameters A_1 and A_2 in the presence of oil films of different physical and physico-chemical properties, which exhibit significant damping-mechanism differences on the short surface waves (see Pogorzelski, 1990b, 1991).

The parameter A_1 is negative in the presence of a Gasoline 86 oil film and displays left-hand asymmetry; A_1 is positive in the presence of the other oil films, and displays right-hand asymmetry (Figs. 3, 4, 5, 6).

In the presence of Gasoline 86 and in the case of a contaminated sea surface the flattening parameter A_2 is negative, which indicates that the distribution is lower than the Gaussian one, *i.e.* the presence of such oil films flattens the distribution; A_2 is positive only in the presence of the Selectol plus oil. This indicates that it had a steeper than Gaussian distribution; the fluctuation coefficient was higher in this case.

It may be concluded from the experimental curves that the presence of an oil layer in the sea surface does not sig ificantly change the probability density function (p.d.f.) of the scattered-signal amplitude distribution (Pogorzelski, 1990a). However, it does lead to apparent changes in the parameters referred to the clean water surface.

It can be seen from Table 1 that the mean amplitude for a surface covered with a light oil film (Gasoline 94; Gasoline 86; and contaminated surface) is low when the percentage error of the scattered signal amplitude is lower than 10%. The second central moment m_2, which may be represented by the standard deviation σ in the presence of Selectol plus oil, is greater than that of light oil films and the clean sea water surface (for a more detailed discussion, see Pogorzelski, 1991).

References

Beckamn P., Spizziching A., 1963, *The Scattering of electromagnetic waves from rough surfaces,* Pergamon Press Ltd.

Clay S. C., 1966, *A relationship between wind stress and wave slope*, J. Geophys. Res., 71, 2037.

Clay S. C., Medwin H., 1964, *High-frequency acoustical reverberation from a rough-sea surface*, J. Acoust. Soc. Am., 36, 11, 2131–2134.

Clay S. C., Medwin H., 1970, *Dependence of spatial and temporal correlation of forward-scattered underwater sound on the surface statistics. I theory*, J. Acoust. Soc. Am., 47, 5, 1412–1418.

Clay S. C., Medwin H., Wright W. M., 1973, *Damping of waves on monolayer-covered surfaces*, J. Acoust. Soc. Am., 53, 6, 1677–1682.

Clay C. S and Medwin H., 1977, *Acoustical oceanography principle and applications*, John Wiley, New York.

Leonard F., 1970, *Survey of literature on reflectio and scattering of sound waves at the sea surface*, J. Acoust. Soc. Am., 47, 5, 1209–1228.

Marsh H. W., Kenne N. M., Ropert L. W., 1955, *Practical physics*, McGraw Hill Book Comp. Inc.

Marsh H. W., Schulkin M., Kneale S. G., 1961, *Scattering of underwater sound by the sea surface*, J. Acoust. Soc. Am., 33, 3, 334–340.

Medwin H., 1967, *Specular scattering of underwater sound from a wind-driven surface*, J. Acoust. Soc. Am., 4, 6, 1485–1495.

Medwin H., Clay C. S., 1970, *Dependence of spatial and temporal correlation of forward-scattered underwater sound on the surface statistic, II experiment*, J. Acoust. Soc. Am., 47, 5, part I, 1419–1429.

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

Pogorzelski S., Linde B., Śliwiński A., 1986, *Interrelationship between the process of surface wave generation caused by air stream and wave attenuation process on water covered with a monolayer of crude oil derivative*, Oceanologia, 24, 29–39.

Pogorzelski S., Linde B., Śliwiński A., 1988, *Analysis of the ultrasounic scattered signal for oil pollution detection on the undulatet water surface*, Proc. 35 Sem. Acoust., part 2, Białowieża, 211–215, (in Polish).

Pogorzelski S., 1989, *An investigation of ultrasound scattering from the sea surface influenced by oil pollutants*, Proc. 6 Symp. Underwater Acoust., Gdańsk, 256–260, (in Polish).

Pogorzelski S., 1989a, *Statistic of underwater acoustic signals scattered by the rough water surface covered with a layer of oil substances*, Oceanologia, 27, 43–60.

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

Pogorzelski S., 1990a, *Remote sensing of the sea oil pollution contamination by means of high frequency surface scattering*, Arch. Acoust., 15, 3–4, 437–446.

Pogorzelski S., 1990b, *Detection of a wavy water surface oil contamination by means of ultrasonic scattering*, Martin–Luther Universität, Halle–Wittenberg, Wiss. Beitr., 26, 61–65.

Pogorzelski S., 1991, *The influence of crude oil spills on the sea surface on ultrasound scattering*, Oceanologia, 31, 107–118.

Welton P. J., Frey H. G., Moore P., 1972, *Experimental measurements of the scattering of acoustic waves by rough surface*, J. Acoust. Soc. Am., 52, 5, part 2, 1553–1563.

Willard B., 1959, *Ocean waves,* W. H. Freeman and Co.