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REMOTE SENSING OF THE SEA OIL POLLUTION BY MEANS OF HIGH FREQUENCY SURFACE SCATTERING(*)

S. J. POGORZELSKI

Environmental Laboratory of Acoustic and Spectroscopy University of Gdańsk
(80-952 Gdańsk, ul. Wita Stwosza 57)

The statistical properties of the ultrasonic signal scattered at a rough surface of both clean water and water covered with a layer of oil substance in an outdoor pond were examined. The results obtained by means of free-floating acoustic buoy-like system confirmed all the laboratory results and predictions of high-frequency scattering theory. The proposed system enables the remote, contactless sensing and determination of the principal physical properties of the oil substance spread on the rough water surface on the basis of scattered signal statistics considerations.

Introduction

An application of acoustic surface scattering as a suitable tool for remote sensing and determination of the sea-atmosphere interaction process has been becoming more and more often used since last ten years [1, 2]. A high-frequency acoustic scattering system (i.e. one with a large value of Rayleigh parameter) enables investigation of small scale processes and objects in the sea like: bottom microrelief [3, 4], wave breaking [1], propagation of capillary waves and surface currents, Langmuir circulation, gas bubbles and plankton population [2]. A layer of an oil substance on the sea surface strongly influences the field of wind waves particularly from short gravity and capillary range [5, 6].

In modern oceanography the study of this variability is closely connected with the problem of remote sensing of ocean processes by their manifestation on the surface. Capillary wind waves are characterized by a particular shape, have a large steepness and small amplitude [7, 8]. In high-frequency scattering, the scattering function of

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the acoustic waves depends only on the mean square slope of the surface [9]. Therefore an acoustic system of such properties constitutes a most suitable tool for investigation of scattering on the surface of the type described. All systematic changes of the rough water surface undulation, for example due to the presence of a layer of oil substance, express themselves in corresponding changes of the scattered signal statistics as shown in the laboratory measurements [10, 11]. The aim of this paper is to present the new acoustic system for remote sensing and monitoring of the surface oil pollution in natural conditions. Some preliminary results of the outdoor pond measurements by means of buoy-like acoustic system and artificial oil slick spread on the surface are also presented. The properties of the used system and obtained results are discussed in terms of high-frequency surface scattering theory [3, 12].

2. Statistical parameters of acoustic signals scattered at rough surface. Theory

Essential characteristics of the fluctuations of the scattered acoustic signal i.e. autocorrelation functions, the magnitude of amplitude fluctuations, and the form of probability density function (p.d.f.) depend on the value of Rayleigh parameter [13, 14]:

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

where $k = 2\pi/\lambda$ – wavenumber of the acoustic wave of length λ, h – height of surface irregularities, θ – incident angle of the acoustic wave.
At small values of $R_a(\ll 1)$, autocorrelation functions of the scattered signal amplitude are identical with the same functions of the undulated surface, and probability density function has the form of Gaussian distribution [13, 14, 15]:

$$p_n(X_a) = \frac{1}{\sqrt{2\pi\sigma}}\exp\left[-(X_a - \bar{X}_a)^2/2\sigma^2\right], \tag{2}$$

where X_a, $\bar{X}_a$ – temporal and mean amplitudes, σ – standard deviation.
At large values of $R_a(\gg 1)$, the periodic character of the signal autocorrelation function is disturbed and does not exhibit any connections with the autocorrelation function of the rough surface. The statistical distribution of signal amplitude has the form of Rayleigh distribution [15, 16, 17]:

$$p_r(X_a) = (X_a/\sigma^2)\exp\left[-X_a^2/2\sigma^2\right]. \tag{3}$$

At intermediate values of R_a, the Rayleigh-Rice distribution, gamma distribution, three-parameter log-normal distributions, etc. are obtained [13, 15, 16, 18]. A variety of the distribution functions observed in many experiments results from different character of wave motion in each case [15].
A good approximation of the experimental distribution is obtained by expanding the Gaussian-distribution into Gram-Charlier series up to the fourth statistical moment

[19]. The p.d.f. of polynomial distribution has the following form [20]:

$$p(X_a) = p_n(X_a)\left[1 + \frac{A_1}{6}H_3(m) + \frac{A_2}{24}H_4(m) + \ldots\right], \qquad (4)$$

where $m = \frac{X_a - \bar{X}_a}{\sigma}$ – normalized random variable, $H_3(m) = m^3 - 3m$, $H_4(m) = m^4 - 6m^2 + 3$ – Hermite's polynomials, $A_2 = (\mu_4/\sigma^4) - 3$ – flattening coefficient, $A_1 = \mu_3/\sigma^3$ – asymmetry coefficient, μ_3, μ_4 – third and fourth central moments. The A_1 and A_2 parameters describe in a regular manner deviations of the experimental distribution from the Gaussian one, in which values of $\bar{X}_a$ and σ are introduced from the experimental data. A fluctuation coefficient is a measure of the signal amplitude variability, and defined by equation [14, 15, 17]:

$$\eta = \sigma/\bar{X}_a. \qquad (5)$$

Fig. 1 presents theoretically computed η (R_a) dependence [17], which has an asymptotic character in the range of large R_a values. A high-frequency acoustic surface scattering is characterized by means of acoustic surface scattering cross section (also called the wave scattering function) [3, 14]:

$$S_{hf} = r^2 I_s/I_0 A, \qquad (6)$$

where I_0, I_s – intensity of the incident and scattered waves, r – distance between the transducer and the center of irradiated surface, A – area of the irradiated surface.

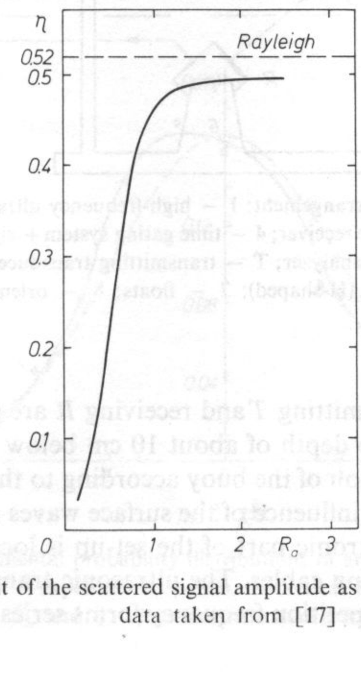

FIG. 1. Fluctuation coefficient of the scattered signal amplitude as a function of Rayleigh parameter with data taken from [17]

S_{hf} depends only on the mean square slope of the rough surface [9], and does not depend on driving wave frequencies, significant wave heights or correlation radius of rough surface undulation.

3. Experimental set-up and methodology

Scattering measurements of the ultrasound waves were carried out in an outdoor pond of small dimensions i.e. 5×5 m, under conditions of wind speed ranging from 0.5 to 2 m/s.

Fig. 2 presents a block diagram of the experimenal arrangement. The ultrasonic

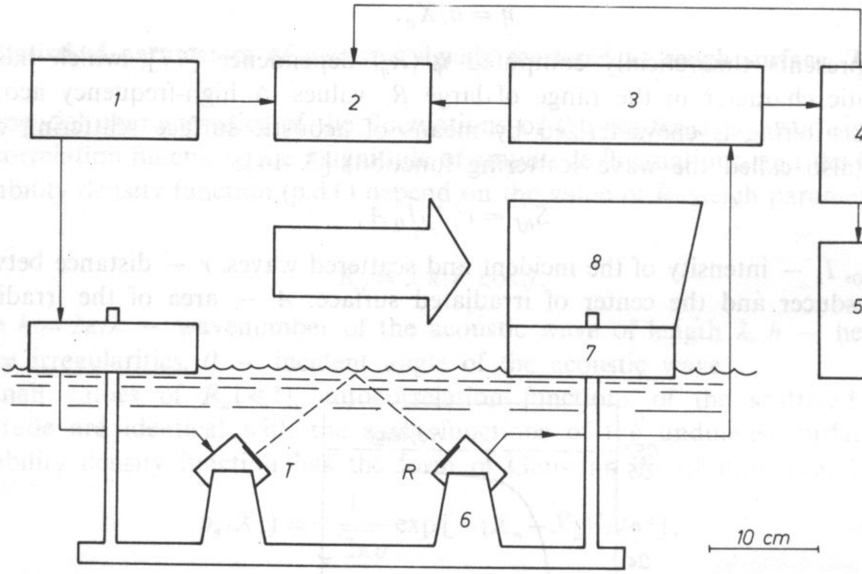

FIG. 2. Diagram of the experimental arrangement: 1 — high-frequency ultrasonic transmitter; 2 — oscilloscope; 3 — high-frequency ultrasonic receiver; 4 — time gating system + signal envelope and peak value detectors; 5 — statistical distribution analyzer; T — transmitting transducer; *R* — receiving transducer; 6 — buoy support (H-shaped); 7 — floats; 8 — orienting wings

quartz transducers: both transmitting *T* and receiving *R* are situated on the support of the free-floating buoy at the depth of about 10 cm below the water surface. Two float wings enable self-orientation of the buoy according to the actual wind direction, which significantly reduces the influence of the surface waves reflected from the floats on the measurement. The electronic part of the set-up is located on the pond bank and connected to the buoy using cables. The ultrasonic transmitter operating under pulse regime with the 3 kHz repetition frequency forms series of pulses lasting few μs.

Each pulse has a rectangular envelope and is filled with a sine wave of 10 MHz frequency. An incident angle of the acoustic beam is equal to 60°. The scattered signal is registered in the specular reflection direction. A time gate of the electronic circuit 4 enables the envelope detection and measurement of peak value of the signal part corresponding only to surface scattering. Then the statistical analysis of the signal was performed using a Statistical Distribution Analyzer (Type 4420, Brüel and Kjaer) which measured the amplitude every 0.1 s and the p.d.f. of signal distribution was determined on the basis of 1800 counts. The scattering measurements were carried out for both clean water surface and water surface covered with a layer of gasoline 96. This gasoline has the following physical properties: density 760 kg/m^3, viscosity 0.6 mPa·s, and surface tension 20.3 mN/m has got of a positive spreading coefficient value against water and spontaneously forms an uniform layer (see Tab. 1 in [10]).

4. Results discussion

Figs 3 and 4 present examples of probability distributions $P(m)$ of amplitudes of the acoustic signal scattered from a rough surface of clean water and water covered with the gasoline 96 film, respectively. They also include two theoretical forms of p.d.f: Rayleigh distribution (solid line) and Gaussian distribution (dotted line), in which $\bar{X}_a$ and σ values are introduced from the experimental data. In order to make the comparison between the experimental distribution and the theoretical ones easier, the distributions are presented as functions of normalized random variable m.

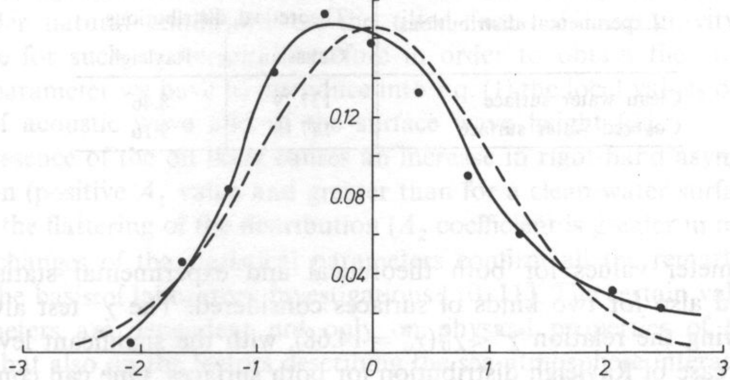

FIG. 3. Theoretical and experimental probability distributions of amplitudes of acoustic signal scattered from a rough water surface. ● — experimental points, theoretical Rayleigh (——) and Gaussian (- - - -) functions, in which $\bar{X}_a$ and σ values are introduced from the experimental data

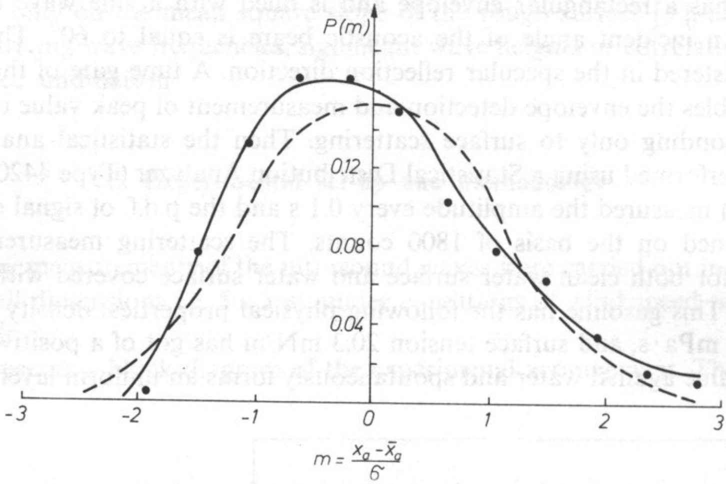

FIG. 4. Theoretical and experimental probability distributions of amplitudes of acoustic signal scattered from a rough water surface covered with a layer of gasoline 96. • – experimental points, theoretical Rayleigh (——) and Gaussian (- - - -) functions, in which $\bar{X}_a$ and σ values are introduced from the experimental data

The experimental points in the case of both surfaces considered are much closer to the Rayleigh distribution than to Gaussian one, which is in agreement with the results of other authors and high-frequency surface scattering theory [12, 13, 15, 18, 21]. This remark can be confirmed by the χ^2 goodness of fit test [20]. Tab. 1 collects

Table 1. Parameters of χ^2 goodness of fit test

Experimental distributions	Theoretical distributions	
	Gaussian	Rayleigh
Clean water surface	137.79	8.46
Covered water surface	147.18	9.16

the χ^2 parameter values for both theoretical and experimental statistical distributions, and also for two kinds of surfaces considered. The χ^2 test always gives results satisfying the relation $\chi^2 < \chi_0^2$ ($\chi_0^2 = 14.68$), with the significant level fixed at 10% only in case of Rayleigh distribution for both surfaces. One can conclude that the presence of oil substance layer on the rough water surface does not significantly change the form of p.d.f. of the scattered signal amplitude, although leads to noticeable changes of the statistical distribution parameters as shown in Table 2. Changes of the statistical parameter values taken into consideration, observed for

Table 2. Statistical parameters of the distribution of the scattered signal amplitudes

Surface	$\bar{X}_a$	η	A_1	A_2
Clean water	0.1876	0.3209	0.4748	−0.2290
Covered water	0.1746	0.3315	0.5126	−0.2946

both clean and covered water surfaces give a quantitative measure of the distribution deviations which can not be simply noticed on visual inspection of Figs. 3 and 4. It can be seen that for the covered surface the mean amplitude is lower and fluctuation coefficient is greater which well corresponds to higher surface wind waves (the rough surface scatters ultrasonic waves more effectively). The water surface covered with the light oil substance film is probably much more susceptible to deformation caused by wind. This substance is characterized by density, viscosity and surface tension much smaller than water. However, such explanation seems to be a bit simplified because of a very complicated influence of the oil slick on the field of wind waves, which also depends on wind-waves range considered. Generally, the presence of oil film suppresses the wind waves from short gravity and capillary range but for waves of decimetre length an opposite effect is observed, and such waves are amplified [5].

The fluctuation coefficient in the case of the both surfaces reaches only slightly over 60 per cent of the asymptotic theoretical value (= 0.5227, see Fig. 1) expected for high-frequency surface scattering. Waves of the height equal to few cm were observed in the pond, which in the case of the applied acoustic system results in Rayleigh parameter values of the order of 100. On the other hand, the measured η values correspond to 0.6–0.7 of asymptotic R_a values. This apparent disagreement can be explained in terms of high-frequency acoustic scattering theory for two-scale composite-roughness surface. One may remember that mainly capillary waves, which occur under natural conditions on the tilted faces of long gravity waves, are responsible for such scattering. Therefore in order to obtain the "true" value of Rayleigh parameter we have to introduce into Eq. (1) the local values of the angle of incident of acoustic wave and of the surface wave height [3].

The presence of the oil layer causes an increase in right-hand asymmetry of the distribution (positive A_1 value and greater than for a clean water surface), and also intensifies the flattering of the distribution (A_2 coefficient is greater in modulus). The observed changes of the statistical parameters confirm all the remarks previously made on the basis of laboratory investigations [10, 11]. The certain values taken by the parameters are dependent not only on physical properties of the given oil substance but also on the factors describing the sea-atmosphere interaction process. For example, the oil slick on the sea surface influences the dissipation rate of wind waves energy [5, 6], vertical wind profile near the surface (see Fig. 9 in [6]), and mean slope of water surface (Eq. (15) in [22]). It may be helpful to add that in the outdoor pond measurements the ratio h/λ (significant wave height to ultrasonic wavelenght) took on values similar, for example, to those of an acoustic experiment with acoustic waves of 80–100 kHz frequency at open sea. Fig. 5 presents a time record of the scattered signal temporal amplitude. The passage of the slick edge is clearly seen (and indicated by the arrow) as a rapid drop of the signal.

FIG. 5. Time record of the scattered signal amplitude. An arrow indicates the passage of the oil slick edge

The signal consists of the short-time oscillations of the frequency ranging from 3 to 15 Hz, which correspond to the gravity-capillary range of wind waves [13]. The spectrum range of the signal fluctuation frequencies is connected with the properties of the used acoustic system, especially with the ratio of linear dimension of the irradiated surface area A to the lenght of surface wave. The area of the irradiated region of elliptic shape is equal to $A = \pi XY = 0.645 \times 10^{-4}$m ($2X = 1.3$ cm and $2Y = 0.6$ cm, see [10]). The value of $2X$ is comparable to the length of surface wave of 30 Hz frequency of the clean water surface (≈ 1.2 cm, [13]). Since the scattered signal is averaged over the whole element of the area A, the dynamics of the recorded signal and sensitivity of the system to changes of surface roughness decreases with an increase of surface wave frequency (decrease of its lenght). It is accepted that the surface waves of the lenght equal to $4X$ and larger are registered with maximum dynamics [12]. The properties of the applied acoustic system allow recording surface waves of frequency of 15 Hz or smaller as shown in Fig. 5.

5. Conclusions

An outdoor pond surface scattering measurements by means of free-floating buoy-like acoustic system showed that a probability density function of the signal amplitude distribution has a Rayleigh form for both clean water surface and water surface covered with oil substance layer. The presence of the oil substance film does not change the signal distribution form although leads to significantly different values of the statistical distribution parameters as compared to the clean surface scattering. The changes in the parameters values are related to physical properties of the oil substance spread on the rough surface as mentioned previously on the basis of the laboratory measurements [10, 11]. The results obtained in a small tank can not be directly applied to situation existing in natural conditions. A reliable acoustic method for remote sensing requires careful and extensive measurements of the air-sea interface properties and other factors describing the interaction process between atmosphere and sea in conjunction with measurements of acoustic scattering. In order to test the system presented here and theory developed in this and previous papers [10, 11], additional experiments with surface films of different chemical, structure have to be performed. The described system seems to be suitable for continuous long-term monitoring for regions not so far from shore at limited state of undulation.

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