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by

WOLFGANG BACHMANN

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A theoretical model for the backscattering strength of a composite-roughness sea surface

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The surface-backscattering strength is calculated according to Rayleigh theory for surface excursions much smaller then the sound wavelength. By taking account of self-shadowing and modulation of grazing angles, the validity of the result is extended to arbitrary roughness. The predictions of this new composite-roughness scattering model are compared with a small set of experimental data.

Subject Classification: 13.6.

INTRODUCTION

The purpose of this paper is to derive a formula for the sound backscattering strength of a sea surface of arbitrary roughness. In long-range sonar applications, only sound rays of small grazing angles (say 0 to 10°) reach the sea surface with high enough intensity to contribute significantly to the surface reverberation. Backscattering at such small grazing angles is strongly influenced by high-excursion, low-frequency surface waves ("swell"), which are much longer than the sound wavelength. As the growth and decay time constants of this low-frequency part of the sea surface spectrum are in the region 1 to 100 hours,[1] the momentary wind speed, to which the high-frequency part of the surface spectrum is directly related, provides little information. Therefore, a reliable formula for predicting backscattering of sonar waves must contain a sea-state-related parameter as well as wind speed. A general method of obtaining such a formula is to apply a composite-roughness sea surface model (e.g., see Kuryanov[2]) to a small-roughness backscattering theory of the Rayleigh (e.g., see Marsh[3]) or Kirchhoff (e.g., see Parkins[4]) type. In this report, the formula is derived by extending Rayleigh theory; the sea-state-related parameter used is the rms slope of the swell. This formula will be used in an active sonar performance model for predicting the surface backscattering intensity as a function of geometry, wind speed, and sea state.

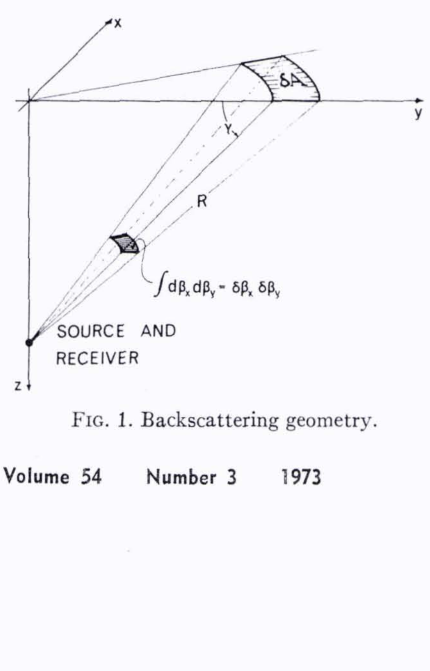

FIG. 1. Backscattering geometry.

I. SURFACE BACKSCATTERING STRENGTH

The backscattering strength q is defined in the manner of Urick[5] as a dimensionless quantity

$$q=\langle i_s\rangle R^2/i_{\rm inc}\delta A, \tag{1}$$

where δA is the illuminated surface area with dimensions much smaller than R (see Fig. 1), $i_{\rm inc}$ is the intensity of incident plane wave, and $\langle i_s\rangle$ is the expected value of intensity of scattered wave at distance R from the illuminated area. Scattering theories usually yield expressions for the "scattering function" Γ, rather than for the backscattering strength q. Therefore, we begin by deriving a relationship between q and Γ.

Γ can be understood as the normalized power spectrum of the scattered wave in the direction cosine domain, i.e., the average "radiation pattern" of the illuminated area on the surface. Thus, we can write

$$\langle i_s\rangle=i_{\rm inc}\int\int\Gamma[\beta_x,\beta_y]d\beta_x d\beta_y, \tag{2}$$

where β_x and β_y are the direction cosines of the scattered wave. The intensity of the scattered field at any point below the surface may then be calculated by integrating over the proper range of β_x and β_y, corresponding to the illuminated area on the surface (see Fig. 1). In the definition of the scattering strength (Eq. 1), the illuminated area is small, so that Γ may be assumed constant over the integration area $\int\beta_x\beta_y$. Inserting Eq. 2 in Eq. 1 gives, then,

$$q=R^2\Gamma\delta\beta_x\delta\beta_y/\delta A. \tag{3}$$

For monostatic backscattering geometry ($\beta_x=\alpha_x=0$;

$\beta_y = -\alpha_y = -\cos\gamma$) it can be shown[6] that

$$d\beta_x d\beta_y / dA = \sin^2\gamma / R^2. \tag{4}$$

Therefore, we obtain from Eq. 3

$$q = \Gamma \sin^2[\gamma]. \tag{5}$$

In the remainder of the section, we develop three alternative forms of Eq. 5, all based on an expression for Γ from Rayleigh theory.

Marsh, Shulkin, and Kneale[6] calculated the scattering function Γ from Rayleigh theory under the assumption of an infinitely extended illuminated surface; their result for $\gamma < 90°$ is

$$\Gamma = 4\alpha_z^2 k^2 h^2 W[\beta_x - \alpha_x, \beta_y - \alpha_y], \tag{6}$$

where k is the wavenumber of incident sound wave $= 2\pi/\lambda$, λ is the sound wavelength, h is rms sea surface displacement, and W is the normalized power spectrum of sea surface displacement, in direction cosine domain. For the monostatic case we obtain

$$\Gamma = 4 \sin^2[\gamma] k^2 h^2 W[0, (-)2\cos\gamma]. \tag{7}$$

It is convenient at this point to change variables from the direction cosine domain to the wavenumber domain. We can write

$$W[\beta_x, \beta_y] = k^2 h^{-2} P_2[\kappa_x, \kappa_y], \tag{8}$$

where $\kappa_x = k\beta_x$ and $\kappa_y = k\beta_y$ are the directional wavenumbers of the surface waves and $P_2[\kappa_x, \kappa_y]$ is the power spectrum of sea surface displacement in wavenumber domain. P_2 is defined as

$$\int_{-\infty}^{\infty}\int P_2[\kappa_x, \kappa_y] d\kappa_x d\kappa_y = h^2. \tag{9}$$

Inserting Eqs. 7 and 8 in Eq. 5 gives

$$q = 4 \sin^4[\gamma] k^4 P_2[0, 2k\cos\gamma]. \tag{10}$$

Equation 10 allows us to calculate (or "predict") the backscattering strength from three physical quantities: grazing angle γ, sound wavenumber k, and directional surface wave spectrum P_2.

It often happens that the surface spectrum can only be measured by nondirectional instruments. It is useful, then, to derive an expression for $q[\gamma]$ for the nondirectional case. If P_2 is assumed to be omnidirectional, then the relation between P_2 and a one-dimensional spectrum P_1 is obtained by transforming the Cartesian coordinates

$$\kappa = (\kappa_x^2 + \kappa_y^2)^{\frac{1}{2}}, \quad \varphi = \arctan(\kappa_y/\kappa_x) \tag{11}$$

and then integrating over φ. The result is

$$P_2[\kappa_x, \kappa_y] = P_1[(\kappa_x^2 + \kappa_y^2)^{\frac{1}{2}}] / (2\pi(\kappa_x^2 + \kappa_y^2)^{\frac{1}{2}}), \tag{12}$$

where

$$\int_0^{\infty} P_1[\kappa] d\kappa = h^2.$$

In terms of P_1, the backscattering strength becomes

$$q = \sin^4[\gamma] k^3 P_1[2k\cos\gamma] / (\pi \cos\gamma). \tag{13}$$

Once having abandoned the directional properties of the sea surface, one might as well go one step further and replace the wavenumber spectrum by a frequency spectrum, which is generally much easier to measure. From the dispersion relation for gravity waves (valid for wavelengths greater than about 5 cm)

$$f^2 = g\kappa / 4\pi^2, \tag{14}$$

where κ is the wavenumber of the surface wave, f is the frequency of the surface wave, and $g = 9.81$ m/sec^2, and from the change of variables

$$S[f] df = P_1[\kappa] d\kappa \tag{15}$$

we obtain

$$P_1[\kappa] = \frac{(g/\kappa)^{\frac{1}{2}}}{4\pi} S\left[\frac{(g\kappa)^{\frac{1}{2}}}{2\pi}\right], \tag{16}$$

where $S[f]$ is the power spectrum of the sea surface displacements in the frequency domain. It is normalized as

$$\int_0^{\infty} S[f] df = h^2. \tag{17}$$

By replacing the spectrum in Eq. 13 by Eq. 16 we obtain

$$q = \frac{g^{\frac{1}{2}} k^{\frac{5}{2}} \sin^4\gamma}{\pi^2 (32 \cos^3\gamma)^{\frac{1}{2}}} S\left[\frac{(2kg\cos\gamma)^{\frac{1}{2}}}{2\pi}\right]. \tag{18}$$

The three formulas[7] for surface backscattering strength q (Eqs. 10, 13, and 18) are considered as valid approximations under the conditions

(1) $\lambda \gg h$;	Rayleigh theory[8],	(19a)
(2) $\delta A \gg \lambda^2$;	Implicit assumption for Eq. 6,	(19b)
(3) $R^2 \gg \delta A$;	Definition of q; Eq. 1,	(19c)
(4) P_2 isotropic;	Assumption for Eqs. 13 and 18,	(19d)
(5) $\lambda > 0.05$ m;	Approximate rule for validity of dispersion relation Eq. 14.	(19e)

As most sonar wavelengths are between 0.1 and 1 m, the condition Eq. 19a is often not fulfilled. The composite structure model developed in the next section circumvents this condition.

II. SURFACE WITH COMPOSITE STRUCTURE

Almost all the energy of a wind-generated sea is concentrated in the low-frequency part of the sea surface power spectrum, say at $f < 0.2$ Hz or $\Lambda > 35$ m. Thus, the large excursions violating Condition 19a are

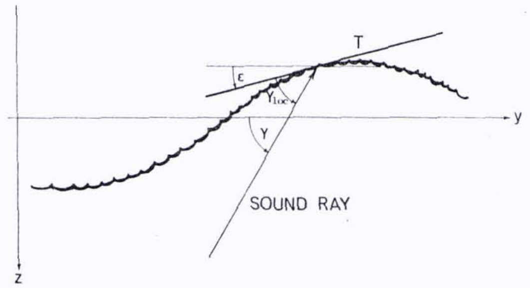

FIG. 2. Modulation of local grazing angle by low-frequency surface wave components (Swell). The local tangent T is inclined by an angle $\bar{\epsilon}$ with respect to the mean surface.

associated with wavelengths much longer than the typical resonant sonar backscattering region (0.1–1 m). This observation leads to the composite structure surface model. The power spectrum of sea surface displacements is divided into two regions, $S_{\text{low}}[f]$ and $S_{\text{high}}[f]$. Small-excursion backscattering theory (i.e., Eq. 18) is applied to $S_{\text{high}}[f]$. The "carrier waves" or "facets" represented by $S_{\text{low}}[f]$ are taken into account by modulation of the local grazing angle (Sec. III) and shadowing of a part of the illuminated surface (Sec. IV).

The choice of the division point f_L appears at first to be highly arbitrary. However, it can be shown that an optimum f_L exists where the sum of finite excursion error and finite facet curvature error is a minimum.[9] In more simple terms the following two conditions for f_L should be fulfilled:

$$\int_{f_L}^{\infty} S_{\text{high}}[f]df \ll \lambda^2 \tag{20}$$

and

$$\frac{1}{\kappa_L}\int_0^{\kappa_L} P_1[\kappa]\kappa d\kappa \gg \lambda^2, \tag{21}$$

where $\kappa_L = 4\pi^2 f_L^2/g$.

Following Phillips,[10] the high-frequency part of the gravity wave spectrum (= "equilibrium range") can be described approximately by

$$S_{\text{high}}[f] = \mu g^2 f^{-5}, \tag{22}$$

where μ is called "Phillips' constant." Its numerical value varies with the normalization of $S[f]$ and with the way of writing Eq. 22.

Inserting this spectrum into Eq. 18, we obtain the simple formula

$$q[\gamma_{\text{loc}}] = \pi^3\mu \tan^4[\gamma_{\text{loc}}], \tag{23}$$

where γ_{loc} is the local grazing angle (see Fig. 2).

Equation 23 differs only by a factor of $\pi/2$ from a similar expression of Marsh,[11] but the interpretations are different. The backscattering strength is here a function of local grazing angle, rather than of the mean (or geometrical) grazing angle; this may change the result considerably at small angles.

III. MODULATION OF GRAZING ANGLES

The modulation effect of the "carrier waves" ($S_{\text{low}}[f]$) is illustrated in Fig. 2. The backscattering strength

$$q[\gamma_{\text{loc}}] = q[\gamma - \epsilon] \tag{24}$$

is fluctuating according to the local distribution of carrier slopes ϵ. But what we measure from large distance is the spatial average $\langle q[\gamma-\epsilon]\rangle_\epsilon$.

Because of the nonlinear relation between q and γ (Eq. 10), the modulation of local grazing angles will increase $\langle q\rangle$. This is formally equivalent to attributing an inclination $\Delta\gamma$ to the mean sea surface. We can write

$$\langle q[\gamma_{\text{loc}}]\rangle_\epsilon = \langle q[\gamma-\epsilon]\rangle_\epsilon = q[\gamma+\Delta\gamma]. \tag{25}$$

We wish to use Eqs. 23 and 25 to obtain an expression for $\Delta\gamma$. Utilizing the MacLaurin series, we find that for small γ

$$\tan^4(\gamma) \approx \gamma^4/4, \tag{26}$$

so that Eqs. 23 and 25 can be written in the form

$$(\gamma+\Delta\gamma)^4 \approx \langle(\gamma-\epsilon)^4\rangle_\epsilon = \gamma^4 - 4\gamma^3\langle\epsilon\rangle + 6\gamma^2\langle\epsilon^2\rangle - 4\gamma\langle\epsilon^3\rangle + \langle\epsilon^4\rangle. \tag{27}$$

To evaluate Eq. 27, we must investigate the statistical behavior of the local inclination (slope), ϵ. We assume that the slopes of long waves in open sea never exceed a few degrees. Thus,

$$\epsilon = \arctan\frac{\partial z}{\partial r} \approx \frac{\partial z}{\partial r}, \tag{28}$$

where z is surface displacement due to the swell and r is a distance coordinate on the mean surface. Viewing the swell as a narrow-band random process (i.e., Rayleigh distribution of amplitude, uniform distribution of phases), z should be nearly normally distributed. Thus, ϵ

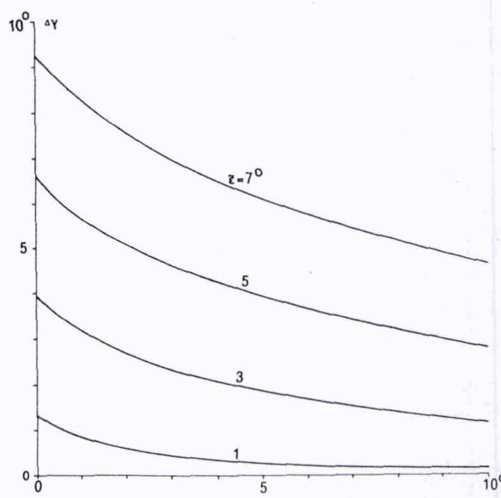

FIG. 3. Pseudo-inclination $\Delta\gamma$ of mean surface, caused by the rms slope $\bar{\epsilon}$ of the low-frequency part $S_{\text{low}}[f]$ ("swell") of the surface spectrum.

is also nearly normally distributed. Since it is natural to assume $\langle\epsilon\rangle = 0$, all odd moments are zero and the even moments are given by

$$\langle\epsilon^{2n}\rangle = (\langle\epsilon^2\rangle)^n \prod_{\nu=0}^{n-1} (1+2\nu). \qquad (29)$$

Now, Eq. 27 reduces to

$$(\gamma+\Delta\gamma)^4 \approx \gamma^4 + 6\gamma^2\langle\epsilon^2\rangle + 3(\langle\epsilon^2\rangle)^2 = \gamma^4(1+6A^2+3A^4), \qquad (30)$$

where

$$A = \bar{\epsilon}/\gamma; \quad \bar{\epsilon} = \text{rms value of } \epsilon.$$

Equation 30 reduces easily to

$$\Delta\gamma = \gamma[(1+6A^2+3A^4)^{\frac{1}{4}} - 1]. \qquad (31)$$

This formula is illustrated in Fig. 3, which shows how the pseudo-inclination $\Delta\gamma$ of the mean surface varies with $\bar{\epsilon}$ and γ. For the case of very small γ (i.e., for γ approaching 0°), it remains finite (corresponding to the fact that γ_{loc} may well be nonzero when γ is zero):

$$\Delta\gamma = 3^{\frac{1}{4}}\bar{\epsilon} \qquad (32)$$

as $\gamma \rightarrow 0$.

For evaluation of Eq. 31, we need an expression for $\bar{\epsilon}$, which could be obtained, with proper precautions,[9] from either of the following

$$\bar{\epsilon}^2 = \int_0^{\kappa_L} \kappa^2 P_{1,\text{low}}[\kappa] d\kappa \qquad (33a)$$

$$= \frac{16\pi^4}{g^2} \int_0^{f_L} f^4 S_{\text{low}}[f] df, \qquad (33b)$$

where κ_L and f_L are related by Eq. 14.

IV. SHADOWING

The phenomenon of shadowing of parts of the surface by its own large scale roughness has been treated in several papers.[12] B. G. Smith,[13] for example, obtained a relatively simple-looking formula, which has been shown to be in close agreement with computer simulations; namely,

$$\sigma[\gamma,\bar{\epsilon}] = \frac{1-\frac{1}{2}\,\text{erfc}B}{1+\frac{1}{2}\pi^{-\frac{1}{2}}B^{-1}\exp - B^2 - \frac{1}{2}\,\text{erfc}B}, \qquad (34)$$

where

$\sigma[\gamma,\bar{\epsilon}]$ = probability that a point on the surface is not shadowed, independent of its coordinates,

$B = \tan[\gamma]/(\bar{\epsilon}\sqrt{2}) \approx 1/(A\sqrt{2})$; for small grazing angles,

and

$$\text{erfc}[x] = 1 - 2\pi^{-\frac{1}{2}} \int_0^x \exp[-t^2] dt.$$

The backscattering strength $q[\gamma+\Delta\gamma]$ has to be multiplied by $\sigma[\gamma,\bar{\epsilon}]$ to take into account the reduction of illuminated area by shadowing (see Eq. 35 below).

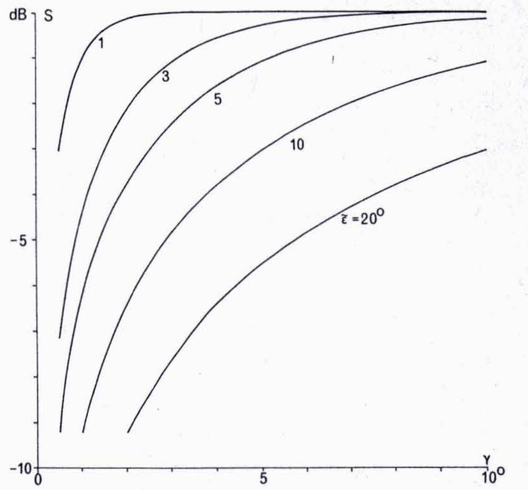

FIG. 4. Smith's shadow function versus grazing angle with rms swell slope as parameter.

$\sigma[\gamma,\bar{\epsilon}]$ is plotted in Fig. 4. One can see that for moderate roughness ($\bar{\epsilon} < 5°$), shadowing can affect $\langle q[\gamma]\rangle$ only at very small grazing angles.

V. COMPARISON WITH EXPERIMENTS

Summarizing, the backscattering strength q, calculated by applying Rayleigh–Marsh theory to the high-frequency part S_{high} of the sea surface spectrum, suffers two modifications due to S_{low}, namely, an equivalent shift $\Delta\gamma$, and a reduction by the shadowing function σ. The complete formula is

$$q[\gamma] = \sigma[\gamma,\bar{\epsilon}] \cdot \tan^4[\gamma + \Delta\gamma[\bar{\epsilon}]] \cdot \pi^3\mu. \qquad (35)$$

The S_{low} contribution is uniquely determined by the rms value $\bar{\epsilon}$ of the local inclinations, through Eqs. 31 and 34. $\bar{\epsilon}$ can be calculated from Eq. 33. The S_{high} contribution is expressed by the Phillips constant, μ, which may vary with wind speed.

A verification of the theoretical model in Eq. 35 has still to be made, with backscattering strength q, and surface spectrum, S_{low} and S_{high}, measured at the same time. Publications have not been found on suitable combinations of acoustical and oceanographical measurements.

However, from a series of SACLANTCEN experiments conducted in the Mediterranean, we may draw some preliminary conclusions. The backscattering strength $q[\gamma]$ has been determined from acoustical data at 3.5 kHz with a rather accurate technique.[14] Together with these acoustical experiments, the low-frequency part S_{low} of the sea surface spectrum was measured and the rms slope of swell, $\bar{\epsilon}$, has been calculated. As S_{high} was not measured, it was attempted to estimate μ using Eq. 35. Since μ is apparently wind dependent, this was done as a function of wind speed, resulting in the

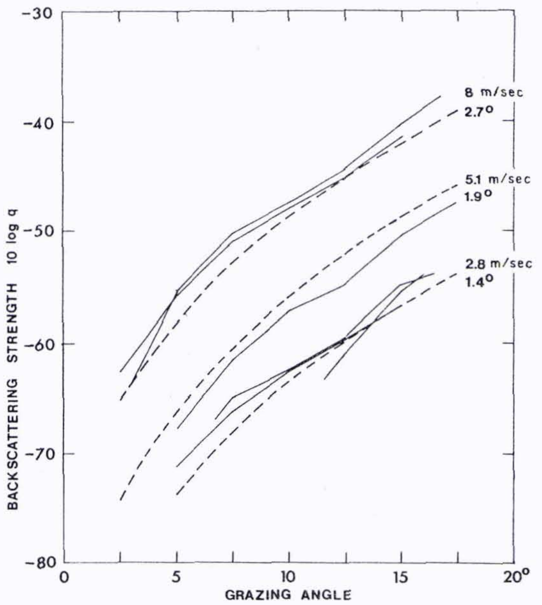

FIG. 5. Prediction and measurements of surface backscattering strength. Curve parameter: wind speed U and rms slope. Dashed lines: Calculated from Eqs. 35 and 36.

empirical formula

$$\mu = 2.2\ 10^{-7}\left(\frac{U}{1\ \text{m/sec}}\right)^{3.5}, \qquad (36)$$

where U is wind speed, measured 18 m above the sea (2.7 m/sec$<U<$8 m/sec). The "Phillips constant" μ is defined in this paper by Eqs. 17 and 22. For comparing Eq. 36 with Phillips' original constant β one should substitute

$$\mu = (2\pi)^{-4}\beta. \qquad (37)$$

As the formula, Eq. 36, was obtained from a relatively small set of data it is not very accurate; e.g., a recent examination of the experimental equipment has shown that the vertical beam pattern of the hydrophone array was about 10% narrower than it had been assumed. Consequently, the numerical factor in Eq. 36 had to be increased by 2.6 with respect to the earlier value.[15] However, there still remains an uncertainty of the order 2.

In the absence of a better verified model, one may use Eq. 36 to insert into Eq. 35 to obtain a simple formula for sea surface backscattering strength $q[\gamma]$ as a function of rms swell slope ϵ and wind speed U. A detailed comparison of this prediction of backscattering strength with those of other authors and with the above mentioned measurements is being prepared for publication.[16] Figure 5 shows an example.

VI. CONCLUSION

The range of validity of Rayleigh theory can be extended considerably by using the composite model of surface structure. The resulting expression for the backscattering strength becomes very simple, when restricted to sound wavelengths of the order 0.1–1 m and to grazing angles below about 10°. The only parameters of this formula, Eq. 35, besides grazing angle, are rms slope of swell and Phillips constant of the small-scale surface waves.

Preliminary results of a series of surface scattering experiments seem to indicate a 3.5th-power relation between wind speed and Phillips constant. If this relation could be verified for a larger range of wind speeds and wavelengths, it would reduce the whole problem of predicting sea surface backscattering strengths to predicting wind speed and rms slope of swell.

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